UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

v.

DECLARATION OF JAMES L. MULLINS, Ph.D.

I, James L. Mullins, hereby declare under penalty of perjury that the following statements made of my own knowledge are true, and that any statements below made on information and belief are believed to be true.

I. INTRODUCTION

1. I am a retired academic librarian working as the Founder and Owner of the firm Prior Art Documentation Librarian Services, LLC at 106 Berrow, Williamsburg, VA 23188. Attached as Appendix A is a true and correct copy of my Curriculum Vitae describing my background and experience. Further information about my firm, Prior Art Documentation Librarian Services, LLC (PADLS), is available at www.priorartdoclib.com.

2. I have been retained by Erise IP, P.A., to authenticate and establish the dates of public accessibility of certain documents for use in one or more *inter partes* review proceedings. For this service, I am being paid my usual hourly fee of $185/hour. My compensation in no way depends on the substance of my testimony or the outcome of the proceeding.

II. BACKGROUND AND QUALIFICATIONS

3. I am presently Dean of Libraries Emeritus and Esther Ellis Norton Professor Emeritus, Purdue University, 2018 – present. I was previously employed as follows:

- Dean of Libraries and Professor & Esther Ellis Norton Professor, Purdue University, West Lafayette, IN, 2004-2017;
- Assistant/Associate Director for Administration, Massachusetts Institute of Technology (MIT) Libraries, Cambridge, MA, 2000-2004.
- University Librarian and Director, Falvey Memorial Library, Villanova University, Villanova, PA, 1996-2000;
- Director of Library Services, Indiana University South Bend, South Bend, IN, 1978-1996. Part-time instructor, School of Library and Information Science, Indiana University, Bloomington, IN, 1979-1996;
- Associate Law Librarian, and associated titles, Indiana University School of Law, Bloomington, IN, 1974-1978; and
- Catalog Librarian, Assistant Professor, Georgia Southern College (now University), Statesboro, GA, 1973-1974.

4. Over the course of my career as a librarian, instructor of library science, author of scholarly publications, and presenter at national and international conferences, I have had experience with catalog records and online library

management systems built around Machine-Readable Cataloging (MARC) standards.

5. In the course of more than forty-four years as an academic librarian and scholar, I have been an active researcher. In my years as a librarian I have facilitated the research of faculty colleagues either directly or through the provision of and access to the requisite print and/or digital materials and services at the universities I worked. I have kept current on the professional library science literature and served on the editorial board of the most prominent library journal, *College and Research Libraries*. This followed service as the chair of the Research Committee of the Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA). As an academic library administrator, I have had responsibility to ensure that students were educated to identify, locate, assess and integrate information garnered from library resources.

III. PRELIMINARIES

6. *Scope of this declaration.* I am not a lawyer, and I am not rendering an opinion on the legal question of whether a particular document is, or is not, a "printed publication" under the law.

7. I am, however, rendering my expert opinion on the authenticity of the document referenced herein and on when and how this document was disseminated or otherwise made available to the extent that persons interested and ordinarily

skilled in the subject matter or art, exercising reasonable diligence, could have located the document by before December 19, 2002.

8. I understand that an item is considered authentic if there is sufficient evidence to support a finding that the item is what it is claimed to be. I also understand that authenticity can be established based on the contents of the documents themselves, such as the appearance, content, substance, internal patterns, or other distinctive characteristics of the item, taken together with all of the circumstances.

9. I understand that a given reference is considered "publicly available" upon a satisfactory showing that such a document has been disseminated or otherwise made available to the extent that persons interested and ordinarily skilled in the subject matter or art exercising reasonable diligence, can locate it. I also understand that materials available in a library constitute printed publications if they are cataloged and indexed according to general library practices that make the references available to members of the interested public.

10. *Materials considered.* In forming the opinions expressed in this declaration, I have reviewed the documents and appendices referenced herein. These materials are records created in the ordinary course of business by publishers, libraries, indexing services, and others. From my years of experience, I am familiar with the process for creating many of these records, and I know these records are

created by people with knowledge of the information in the record. Further, these records are created with the expectation that researchers and other members of the public will use them. All materials cited in this declaration and its appendices are of a type that experts in my field would reasonably rely upon and refer to in forming their opinions.

11. *Persons of ordinary skill in the art.* It is my understanding that the subject matter of this proceeding relates to a cellular communication system. I understand that a "person of ordinary skill in the art at the time of the inventions" is a hypothetical person who is presumed to be familiar with the relevant field and its literature at the time of the inventions. This hypothetical person is also a person of ordinary creativity, capable of understanding the scientific principles applicable to the pertinent field. It is my understanding that persons of ordinary skill in this subject matter or art would have had at least (1) at least an undergraduate degree in electrical engineering (2) a working knowledge of wireless communication systems; and (3) three or more years of experience (or with a graduate degree in the above-stated fields, one or more years of experience) in wireless communication systems.

12. It is my opinion that such a person would have been engaged in academic research, learning through study and practice in the field and possibly through formal instruction the bibliographic resources relevant to his or her research. Since the 1980s such a person would have had access to a vast array of print

resources in distributed systems and/or network applications as well as to a fast-changing set of online resources.

13. *Library catalog records.* Some background on MARC formatted records, OCLC, OCLC Connexion, and WorldCat is needed to understand the library catalog records discussed in this declaration.

14. Libraries world-wide use the MARC format for catalog records; this machine-readable format was developed by the Library of Congress in the 1960s.

15. MARC formatted records provide a variety of subject access points based on the content of the document being cataloged. All subject headings may be found in the MARC fields 6XX. For example, MARC Field 600 identifies personal names used as subjects and the MARC Field 650 identifies topical terms. A researcher might discover material relevant to his or her topic by a search using the terms employed in the MARC Fields 6XX.

16. The MARC Field 040, subfield a, identifies the library or other entity that created the original catalog record for a given document and transcribed it into machine readable form. The MARC Field 008 identifies the date when this first catalog record was entered on the file. This date persists in all subsequent uses of the first catalog record, although newly-created records for the same document, separate from the original record will show a new date. It is not unusual to find multiple catalog records for the same document

17. WorldCat is the world's largest public online catalog, maintained by the Online Computer Library Center, Inc., or OCLC, and built with the records created by the thousands of libraries that are members of OCLC. WorldCat provides a user-friendly interface for the public to use MARC records; it requires no knowledge of MARC tags and codes. WorldCat is easily accessible through the World Wide Web to all who wish to search it; there are no restrictions to be a member of a particular community, etc. The date a given catalog record was created (corresponding to the MARC Field 008) appears in some detailed WorldCat records as the Date of Entry but not necessarily all.

18. Whereas WorldCat records are widely available, the availability of MARC formatted records varies from library to library.

19. When an OCLC participating institution acquires a document for which it finds no previously created record in OCLC, or when the institution chooses not to use an existing record, it creates a record for the document using OCLC's Connexion, the bibliographic system used by catalogers to create MARC records. Connexion automatically supplies the date of record creation in the MARC Field 008. In the 040 field, the code for the member library is inserted to indicate what library created the record.

20. Once the MARC record is created by a cataloger at an OCLC participating member institution, it becomes available to other OCLC participating

members in Connexion and in WorldCat, where persons interested and ordinarily skilled in the subject matter or art, exercising reasonable diligence, can locate it.

Periodical publications

21. A library typically creates a catalog record for a periodical publication when the library receives its first issue. When the institution receives subsequent issues/volumes of the periodical, the issues/volumes are checked in (often using a date stamp), added to the institution's holding records, and made available very soon thereafter – normally within a few days of receipt or (at most) within a few weeks of receipt.

22. The initial periodicals MARC record will sometimes not reflect all subsequent changes in publication details (including minor variations in title, etc.).

Indexing

23. A researcher may discover material relevant to his or her topic in a variety of ways. One common means of discovery is to search for relevant information in an index of periodical and other publications. Having found relevant material, the researcher will then normally obtain it online, look for it in libraries, or purchase it from the publisher, a bookstore, a document delivery service, or other provider. Sometimes, the date of a document's public accessibility will involve both indexing and library date

information. Date information for indexing entries is, however, often unavailable. This is especially true for online indices.

24. Indexing services use a wide variety of controlled vocabularies to provide subject access and other means of discovering the content of documents. The formats in which these access terms are presented vary from service to service.

25. Online indexing services commonly provide bibliographic information, abstracts, and full-text copies of the indexed publications, along with a list of the documents cited in the indexed publication. These services also often provide lists of publications that cite a given document. A citation of a document is evidence that the document was publicly available and in use by researchers no later than the publication date of the citing document.

26. One such index is IEEE Xplore Digital Library. The Institute of Electrical and Electronics Engineers is the world's largest organization for the advancement of technology, with some 430,000 members in 160 countries. Known by its acronym IEEE, it has created IEEE Xplore Digital Library, which provides access to the contents of over 170 journals, more than 1,400 conference proceedings, some 5,100 technical standards, 2,000 eBooks, and 400 educational courses. More than 3 million documents, dating from 1872, are searchable and available either through subscription or individual purchase.

IV. OPINION REGARDING INDIVIDUAL DOCUMENT

Paul Bender, et al., "CDMA/HDR: A Bandwidth-Efficient High -Speed Wireless Data Service for Nomadic Users," IEEE Communications Magazine. Volume 38, Number 7 (July 2000): 70-77.

Authentication

27. Bender refers to a research paper by Paul Bender and others titled "CDMA/HDR: A Bandwidth-Efficient High-Speed Wireless Data Service for Nomadic Users" published in IEEE Communications Magazine, volume 38, number 7 (July 2000) pages 70-77. I requested a copy of the Bender article from the Wisconsin Tech Services (WTS). WTS provided scans from a paper copy held in the Kurt F. Wendt Library, College of Engineering, UW-Madison.

24. Exhibit 1A is a true and accurate copy of the Bender paper from the print copy owned by the Kurt F. Wendt Library, College of Engineering, UW-Madison. Exhibit 1A includes the print issue cover, title page, publication information, table of contents pages, and the Bender article.

25. On the page following the cover of the issue is the ownership and date stamp of the Kurt F. Wendt Library, College of Engineering, UW-Madison, with a check-in date of **July 12, 2000.**

26. Exhibit 1A is in a condition that creates no suspicion about its authenticity. Specifically, the Bender paper in Exhibit 1A is not missing any intermediate

pages of the article's text, the text on each page appears to flow seamlessly from one page to the next, and there are no visible alterations to the document. Exhibit 1A was found within the custody of a library – a place where, if authentic, it would likely be found.

27. The Bender paper is available on-line through IEEE Xplore. Attachment 1B is a print of the Bender paper as retrieved from IEEE Xplore through the Purdue University Libraries on August 5, 2018. https://ieeexplore-ieee-org.ezproxy.lib.purdue.edu/stamp/stamp.jsp?tp=&arnumber=852034

28. I conclude, based on finding Bender in print and held by a research library, University of Wisconsin – Madison, and also available within the IEEE Xplore database, that the Bender paper is an authentic document, and that Exhibit 1A and Exhibit 1B are authentic copies of the Bender paper. From my more than forty years of professional experience the availability it would be expected that the Bender paper would be available within the University of Wisconsin Library within a few days to no more than a week after check-in on July 12, 2000, therefore, no later than July 19, 2000.

Public Accessibility

29. Attachment 1C to my Declaration is a true and accurate copy of the record in OCLC WorldCat for IEEE Communications Magazine. This journal was

first published in 1963 by IEEE Communications Society. WorldCat indicates that 641 libraries hold this title world-wide as of August 2018. Attachment 1C indicates that IEEE Communications Magazine was cataloged in a meaningful way— by subject as well as by title: Telecommunications – Periodicals; Telecommunication. Thus, in my opinion, IEEE Communications Magazine was sufficiently accessible to the public interested in the art that an ordinarily skilled researcher, exercising reasonable diligence, would have had no difficulty finding copies of IEEE Communications Magazine.

30. Exhibit 1A from the University of Wisconsin Library, includes a library date stamp indicating that the July 2000 issue of IEEE Communications Magazine was processed on July 12, 2000. Based on my substantial professional experience of more than forty years, I affirm this date stamp has the general appearance of date stamps that libraries have long affixed to periodicals in processing them into a library's holdings. I do not see any indications or have any reason to believe this date stamp was affixed by anyone other than library personnel on or about the date indicated by the stamp.

31. Exhibit 1D to my Declaration contains the public catalog record (OPAC) from the University of Wisconsin – Madison Libraries for the journal title IEEE Communications Magazine.

32. The UW Library OPAC record (Exhibit 1D) indicates that UW library has subscribed to IEEE Communications Magazine since vol 17, no. 1 (January 1979) to the present. The holdings record located to the right of the OPAC record under heading: "The Library Has" indicates it has print volumes v.38: no.7 (2000, July) through v.40: no 12 (2002, December) this confirms the holding of Volume 38, no. 7, July 2000 from which Exhibit 1A was scanned by WTS and sent to me.

33. Exhibit 1E to my declaration is an article by Elvino S. Sousa titled "Highly Sectorized System for Internet Wireless Access" published in Wireless Communications and Networking Conference 2000, WCNC. 2000 IEEE, vol.1, pp.153-158. Exhibit 1E was downloaded by me from IEEE Xplore on August 5, 2018. On page 157, in References, the first reference is to Bender indicating that Bender was publicly accessible to be cited in a paper presented in Chicago, Illinois, at a conference held September 23-28, 2000.

Conclusion

34. Based on the evidence presented here—publication in the widely held periodical, library processing and cataloging and availability in a research database, IEEE Xplore —it is my opinion that Bender is an authentic document. It is also my opinion that the Bender paper was publicly accessible no later than mid-July 2000.

V. CONCLUSION

35. In summary, I have concluded that the Bender paper is an authentic document that was publicly accessible in libraries no later than mid-July 2000.

36. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner or its expert(s) may raise and to take into account new information as it becomes available to me.

37. I declare that all statements made herein of my knowledge are true, and that all statements made on information and belief are believed to be true, and that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Executed on August 14, 2018 in Williamsburg, Virginia.

James L. Mullins, PhD

APPENDIX A

JAMES L. MULLINS

Prior Art Documentation Librarian Services, LLC

106 Berrow, Williamsburg, VA 23188

jlmullins@priorartdoclib.com

ph. 765 479 4956

Experience:

2018-present	Dean of Libraries Emeritus and Esther Ellis Norton Professor Emeritus
2011-2017	Dean of Libraries & Esther Ellis Norton Professor
2004-2011	Dean of Libraries & Professor Purdue University, West Lafayette, IN.
2000-2004	Assistant/Associate Director for Administration, MIT Libraries, Massachusetts Institute of Technology, Cambridge, MA.
1996-2000	University Librarian & Director, Falvey Memorial Library. Villanova University, Villanova, PA.
1978-1996	Director of Library Services, Indiana University South Bend.
1974-1978	Associate Librarian, Indiana University Bloomington, School of Law.
1974-1978	Instructor/Catalog Librarian. Georgia Southern College (now University).

Teaching Experience:

1977-1996	Associate Professor (part-time), School of Library and Information Science, Indiana University. Subjects taught: Cataloging, Management, and Academic Librarianship.

Education:

The University of Iowa. Honors Bachelor of Arts in History, Religion and Political Science.

The University of Iowa. Master of Arts in Library Science.

Indiana University. Doctor of Philosophy. Concentration: Academic Library Administration. Emphasis: Legal Librarianship.

Awards and Recognition:

2017 Wilmeth Active Learning Center/Library of Engineering and Science, Grand Reading Room, was announced by President Mitch Daniels, Purdue University, that it would be re-named the James L. Mullins Reading Room to honor his leadership and reputation in the academic library profession. September 2017. Portrait unveiled December 2017.

2017 Distinguished Alumnus Award by the School of Informatics and Computing, Indiana University, Bloomington. Given June 25, 2017.

2016 Hugh C. Atkinson Memorial Award, jointly sponsored by the four divisions of the American Library Association (ALA), June 27, 2016.

2015 ACRL Excellence in University Libraries Award, April 23, 2015.

Named Esther Ellis Norton Professor of Library Science by Purdue Trustees, December 11, 2011.

International Review Panel to evaluate the University of Pretoria Library, February 20 – 24, 2011. Pretoria, South Africa.

Publications: (selected)

A Purdue Icon: creation, life, and legacy, edited by James L. Mullins, Founder's Series, Purdue University Press, 138pp., August 2017.

"The policy and institutional framework." In *Research Data Management, Practical Strategies for Information Professionals,* edited by Ray, J M. Purdue University Press, pp.25-44, 2014.

“DataCite: linking research to data sets and content.” In Benson, P and Silver, S. *What Editors Want: An Author’s Guide to Scientific Journal Publishing*. University of Chicago Press, pp. 21-23, December 2012.

“Library Publishing Services: Strategies for Success,” with R. Crow, O. Ivins, A. Mower, C. Murray-Rust, J. Ogburn, D Nesdill, M. Newton, J. Speer, C. Watkinson. *Scholarly Publishing and Academic Resources Coalition (SPARC),* version 2.0, March 2012.

“The Changing Definition and Role of Collections and Services in the University Research Library.” *Indiana Libraries,* Vol 31, Number 1 (2012), pp.18-24.

“Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?” *Journal of Library Administration.* Volume 52, Issue 1, 2012, p. 124-132

Baykoucheva, Svetla. What Do Libraries Have to Do with e-Science?: An Interview with James L. Mullins, Dean of Purdue University Libraries. Chem. Inf. Bull. [Online] 2011, 63 (1), 45-49. http://www.acscinf.org/publications/bulletin/63-1/mullins.php (accessed Mar 16, 2011).

“The Challenges of e-Science Data-set Management and Scholarly Communication for Domain Sciences and Technology: a Role for Academic Libraries and Librarians,” chapter in, *The Digital Deluge: Can Libraries Cope with e-Science?”* Deanna B. Marcum and Gerald George, editors, Libraries Unlimited/Teacher Ideas Press, 2009. (a monograph publication of the combined proceedings of the KIT/CLIR proceedings).

“Bringing Librarianship to e-Science,” *College and Research Libraries.* vol. 70, no. 3, May 2009, editorial.

“The Librarian’s Role in e-Science” *Joho Kanri (Journal on Information Processing and Management),* Japan Science and Technology Agency (formerly Japan Information Center of Science and Technology), Tokyo, Japan. Translated into Japanese by Taeko Kato. March 2008.

The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians,” KIT (Kanazawa Institute of Technology)/CLIR (Council of Library and Information Resources) International Roundtable for Library and Information Science, July 5-6, 2007.

Developments in e-science status quo and the challenge, The Japan Foundation, 2007.

"An Administrative Perspective," Chapter 14, *Proven Strategies for Building an Information Literacy Program*, Susan Curzon and Lynn Lampert, editors, Neal-Schuman Publishers, Inc., New York, 2007. pp. 229-237.

Library Management and Marketing in a Multicultural World, proceedings of the IFLA Management and Marketing (M&M) Section, Shanghai, China, August 16-17, 2006, edited. K.G. Saur, Munchen, Germany, June 2007. 390 pp.

Top Ten Assumptions for the Future of Academic Libraries and Librarians: a report from the ACRL Research Committee, with Frank R. Allen and Jon R. Hufford. *College & Research Libraries,* April 2007, vol.68, no.4. pp.240-241, 246.

To Stand the Test of Time: Long-term Stewardship of Digital Data Sets in Science and Engineering. A report to the National Science Foundation from the ARL Workshop on New Collaborative Relationships: the Role of Academic Libraries in the Digital Data Universe. September 26-27, 2006, Arlington, VA. p.141. http://www.arl.org/bm~doc/digdatarpt.pdf

"Enabling Interaction and Quality in a Distributed Data DRIS," *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS. Leuven University Press, 2006. pp.55-62. Editors: Anne Garns Steine Asserson and Eduard J. Simons.

"Standards for College Libraries, the final version approved January 2000," prepared by the ACRL College Libraries Standards Committee (member), *C&RL News*, March 2000, p.175-182.

"Standards for College Libraries: a draft," prepared by the ACRL College Libraries Section, Standards Committee (member), *C&RL News*, May 1999, p. 375-381.

"Statistical Measures of Usage of Web-based Resources," *The Serials Librarian*, vol. 36, no. 1-2 (1999) p. 207-10.

"An Opportunity: Cooperation between the Library and Computer Services," in *Building Partnerships: Computing and Library Professionals.* Edited by Anne G. Lipow and Sheila D. Creth. Berkeley and San Carlos, CA, Library Solutions Press, 1995. p. 69-70.

"Faculty Status of Librarians: A Comparative Study of Two Universities in the United Kingdom and How They Compare to the Association of College and Research Libraries Standards, " in *Academic Librarianship, Past, Present, and Future: a Festschrift in Honor of David Kaser.* Englewood, Colorado; Libraries Unlimited, 1989. p. 67-78. Review in: *College & Research Libraries,* vol. 51, no. 6. November 1990, p. 573-574.

Presentations: (Representative)

"How Long the Odyssey? Transitioning the Library and Librarians to Meet the Needs and Expectations of the 21st Century University," David Kaser Lecture, School of Informatics & Computing, Indiana University, Bloomington, IN, November 16, 2015.

Presentation at University of Cape Town, Cape Town, South Africa, August 20, 2015.

"The Challenge of Discovering Science and Technology Information," Moderator, International Federation of Library Associations (IFLA) Science and Technological Libraries Section Program, Cape Town, South Africa, August 18, 2015.

"An Odyssey in Data Management: Purdue University," International Federation of Library Associations (IFLA) Research Data Management: Finding Our Role – A program of the Research Data Alliance, Cape Town, South Africa, August 17, 2015.

Presentation at University of Pretoria, Pretoria, South Africa, August 11, 2015.

Co-Convener with Sarah Thomas, Harvard University, at the Harvard Purdue Symposium on Data Management, Harvard University, Cambridge, MA, June 15-18, 2015.

"Strategic Communication," panel discussion on the Director's role and perspective on library communications at Committee on Institutional Cooperation (CIC) Center for Library Initiatives (CLI) Annual Conference, University of Illinois Urbana-Champaign, May 20, 2015.

"Issues in Data Management," panel discussion moderated by Catherine Woteki, United States Undersecretary for Research, Education & Economics at 20th Agriculture Network Information Collaborative (AgNIC) Annual Meeting in the National Agricultural Library, Beltsville, MD, May 6, 2015.

“Active learning/IMPACT & the Active Learning Center at Purdue University,” Florida Institute of Technology, Melbourne, FL, February 11, 2015.

“Science+art=creativity: libraries and the new collaborative thinking,” panel moderator, International Federation of Library Associations (IFLA) 80th General Conference and Assembly, Lyon, France, August 19, 2014.

“Purdue University The Active Learning Center—A new concept for a library,” Association of University Architects 59th Annual National Conference, University of Notre Dame, South Bend, IN, June 23, 2014.

“Big Data & Implications for Academic Libraries,” keynote speaker, Greater Western Library Alliance (GWLA) Cyber-infrastructure Conference, Kansas City, MO, May 28, 2014.

“Research Infrastructure,” panel moderator, Association of Research Libraries (ARL) 164th Membership Meeting, Ohio State University, Columbus, OH, May 7, 2014.

“An Eight Year Odyssey in Data Management: Purdue University,” International Association of Scientific and Technological University Libraries (IATUL) 2013 Workshop Research Data Management: Finding Our Role, University of Oxford, UK, December 2013.

“Purdue University Libraries & Press: from collaboration to integration,” Ithaka Sustainable Scholarship, The Evolving Digital Landscape: New Roles and Responsibilities in Higher Education, libraries as publishers, New York, New York, October 2013.

“Tsinghua and Purdue: Research Libraries for the 21st Century,” Tsinghua University, Tsinghua, China, August 2013.

“Purdue Publishing Experience in the Libraries Publishing Coalition,” Association of American University Presses Annual Meeting, Press-Library Coalition Panel, Boston, Massachusetts, June 21, 2013.

“Indiana University Librarians Day: Purdue University Libraries Ready for the 21st Century,” Indiana University Purdue University Indianapolis (IUPUI), June 7, 2013.

“Purdue University Libraries and Open Access; CNI Project Update,” Coalition for Networked Information, San Antonio, TX, April 5, 2013.

Memorial Resolution, honoring Joseph Brannon, to the Board of the Association of College & Research Libraries, Seattle, WA, January 2013.

"An overview of sustaining e-Science collaboration in an Academic Research Library—the Purdue experience," Duraspace e-Science Institute webcast, October 17, 2012.

"The Role of Libraries in Data Curation, Access, and Preservation: an International Perspective, " Panel Moderator, 78th General Conference and Assembly, International Federation of Library Associations, Helsinki, Finland, August 15, 2012.

"21st Century Libraries," moderator of First Plenary Session, International Association of Technological University Libraries 33rd Annual Conference, Singapore, June 4, 2012.

"Planning for New Buildings on Campus," panel presenter, University of Calgary Building Symposium on Designing Libraries for the 21st Century, Calgary, Alberta, Canada, May 17, 2012.

"Data Management and e-Science, the Purdue Response." Wiley-Blackwell Executive Seminar-2012, Washington, DC, March 23, 2012.

"An overview of Sustaining e-Science Collaboration in Academic Research Libraries and the Purdue Experience." Leadership & Career Development Program Institute, Association of Research Libraries (ARL). Houston, TX, March 21, 2012.

"An overview of Data Activities at Purdue University in response to Data Management Requirements." Coalition for Academic Scientific Computation (CASC). Arlington, VA, September 8, 2011.

"Getting on Track with Tenure," Association of College and Research Libraries (ACRL) Research Program Committee. Washington, DC, June 26, 2011.

"Integration of the Press and Libraries Collaboration to Promote Scholarly Communication," Association of Library Collections & Technical Services (ALCTS) Scholarly Communication Interest Group – American Library Association, New Orleans, Louisiana, June 25, 2011.

"Cooperation for improving access to scholarly communication," with N. Lossau (Germany), C. Mazurek (Poland), J. Stokker (Australia), panel moderator and presenter, Second Plenary Session, International Association of Scientific and

Technological University Libraries (IATUL) 32nd Conference 2011, Warsaw, Poland. May 29-June 2, 2011.

"Riding the Wave of Data," STM Annual Spring Conference 2011. Trailblazing & transforming scholarly publishing **2011**. Washington, D.C., April 28, 2011.

"Confronting old assumptions to assume new roles: physical and operational integration of the Press and Libraries at Purdue University," keynote speaker, 2011 BioOne Publishers & Partners Meeting. Washington, D. C., April 22, 2011.

"Are MLS Graduates Being Prepared for the Changing and Emerging Roles that Librarians must now assume within Research Libraries?" University of Oklahoma Libraries Seminar, March 4, 2011, Oklahoma City, Oklahoma.

"The Future Role of University Librarians," the University of Cape Town, South Africa, February 25, 2011.

"New Roles for Librarians: the Application of Library Science to Scientific/Technical Research – Purdue University – a case study. International Council for Science and Technology (ICSTI); Ottawa, Canada. June 9, 2009.

"Reinventing Science Librarianship: Models for the Future," Association of Research Libraries / Coalition for Networked Information. October 16-17th, 2008, Arlington, VA. Moderator and convener of Data Curation: Issues and Challenges.

"Practical Implementation and Opportunities Created at Purdue University," African Digital Curation Conference, Pretoria, South Africa, (live video transmission), February 12, 2008.

Keynote speaker. "*Scholarly Communication & Academe: The Winter of Our Discontent,"* XXVII Charleston Conference on Issues in Book and Serial Acquisition, Charleston, South Carolina. November 8, 2007.

Keynote speaker. "*Enabling Access to Scientific & Technical Data-sets in e-Science: a role for Library and Archival Sciences,"* Greater Western Library Alliance (GWLA), Tucson, Arizona. September 17, 2007. A meeting of library directors and vice presidents for research of member institutions.

"*The Challenge of e-Science Data-set Management to Domain Sciences and Engineering: a Role for Academic Libraries and Librarians,"* KIT (Kanazawa Institute of Technology)/CLIR (Council of Library and Information Resources)

International Roundtable for Library and Information Science, July 5-6, 2007. Invited to participate by the Deputy Librarian of Congress.

International Association of Technological University Libraries (IATUL), Stockholm, Sweden. June 8, 2007**.** Invited paper**,** *Enabling International Access to Scientific Data-sets: creation of the Distributed Data Curation Center (D2C2).*

"A New Collaboration for Librarians: The Principles of Library and Archival Sciences Applied to the Curation of Datasets," Symposium of the Libraries and the College of Engineering, University of Louisville, April 6, 2007.

"Purdue University Libraries: Through Pre-eminent Innovation and Creativity, Meeting the Challenges of the Information Age," Board of Trustees, Purdue University, February 15, 2007.

ARL Workshop on New Collaborative Relationships: The Role of Academic Libraries in the Digital Data Universe, September 26-27, 2006, Arlington, VA. Invited participant.

NARA and SDSC: A partnership. A panel before the National Science Foundation, June 27, 2006. Arlington, VA. Invited participant.

"Kaleidoscope of Scientific Literacy: fusing new connections," with Diane Rein, American Library Association, Association of College and Research Libraries, Science & Technology Section, Annual Conference, New Orleans, June 26th, 2006.

"Leadership for Learning: Building a Culture of Teaching in Academic Libraries – an administrative perspective," American Library Association, Association of College and Research Libraries, Instruction Section, Annual Conference, New Orleans, June 25th, 2006.

"Building an interdisciplinary research program in an academic library: how the Libraries' associate dean for research makes a difference at Purdue University," International Association of Technological University Libraries (IATUL), Porto, Portugal, May 23rd, 2006.

"Enabling Interaction and Quality in a Distributed Data DRIS," *Enabling Interaction and Quality: Beyond the Hanseatic League*. 8th International Conference on Current Research Information Systems, with D. Scott Brandt and Michael Witt. Promoted by euro CRIS, Bergen, Norway, May 12th, 2006, Brandt and Witt presented in person

"Interdisciplinary Research," with D. Scott Brandt, Coalition for Networked Information (CNI) Spring Meeting: Project Briefing, Washington, D.C., April 3rd, 2006.

"An Interview with Purdue's James Mullins," a podcast submitted by Matt Pasiewicz, on *Educause Connect*, http://connect.educause.edu/James_L_Mullins_Interview_CNI_2005

"Managing Long-Lived Digital Data-sets and their Curation: Interdisciplinary Policy Issues," Managing Digital Assets Forum, Association of Research Libraries (ARL), Washington, D.C., October 28th, 2005.

"The Odyssey of a Librarian." Indiana Library Federation (ILF), District 2 Meeting, South Bend, Indiana. October 4th, 2005.

"New College Library Standards," Standards Committee Presentation, ALA, Chicago, July 7, 2000.

SUNY Library Directors, Lake George, New York. "*The College Library Standards: a Tool for Assessment.*" April 5, 2000.

Tri-State College Library Association, *Finding You Have Talents You Never Knew You Had*, Penn State Great Valley, March 25, 2000.

Using Web Statistics, American Library Association, New Orleans, June 24, 1999.

Keynote speaker at the JSTOR Workshop, January 29, 30, 1999. University of Pennsylvania, Philadelphia, PA.

"The New Standards for Electronic Resources Statistics," Society of Scholarly Publishers, Washington, D.C., September 17, 1998.

"Evaluating Online Resources: Now that you've got them what do you do?," joint presenter with Chuck Hamaker, LSU, at the NASIG Conference, Boulder, Colorado. June 1998.

"What Employers Are Looking for in New Librarians?" Pennsylvania Library Association, Philadelphia. September 26, 1997.

"The Theory of Matrix Management" panel presentation of the Comparative Library Organization Committee of the Library Organization and Management Section of the Library Administration and Management Association, a division of the American Library Association, Annual Meeting, Chicago, June 24, 1990.

Professional Involvement: (summary of recent emphasis)

The focus for my professional involvement and research has moved recently toward managing massive data-sets. This has resulted in working with faculty in the sciences and technology to determine how librarians can collaborate in managing, curating, and preserving data-sets for future access and documentation. This has included various speaking opportunities as well as participation in planning with the National Science Foundation (NSF) on ways in which librarians can be integrated more completely into the funded research process. Participation in the Kanazawa Institute of Technology/Council of Library Resources Roundtable was particularly rewarding and provided new opportunities to share with international colleagues the issues surrounding data-set management. I was the champion for the creation of the Distributed Data Curation Center (D2C2) at Purdue University (http://d2c2.lib.purdue.edu/)

Throughout my career, beginning with my dissertation, I have been actively involved with assessing and evaluating libraries. In the fall of 1999, I contacted twenty-two academic library directors to determine whether the need was also felt by others. The response was overwhelmingly affirmative. This resulted in a meeting at ALA Midwinter, January 2000. A formal meeting followed at Villanova University in April 2000. As convener, I helped to form the University Libraries Group (ULG), modeled after the Oberlin Group for college libraries. The ULG is made up of university libraries that support diverse wide-ranging programs through doctoral level and have a level of support that places them in the top tier of academic institutions. A few of the member libraries, along with Villanova, are William and Mary, Wake Forest, Lehigh, Carnegie-Mellon, Tufts, Marquette, Miami of Ohio, and Southern Methodist.

In 1994 appointed to the Standards Committee, College Section, Association of College and Research Libraries. During the next six years, the Committee concentrated on changing the focus of the standards from quantitative analysis of input and output factors to emphasis on assessment of the outcome. Culmination of the work was a re-issue of the *Standards for College Libraries* in 2000. The knowledge gained through my work experience enabled me to formulate the changes needed in the standards. This work allowed for close collaboration with accrediting agencies, both professional and regional.

During this same time another focus emerged, the impact of digital resources. Through my work on the JSTOR Statistics Task Force, standards were developed on the collection of use of electronic databases. This Standard was later adopted in 1998 by the International Consortium of Library Consortia (ICOLC).

In 2002, the American Library Association appointed me to serve as the liaison to the Marketing and Management Section of the International Federation of Library Associations (IFLA).

Professional Service: (representative list)

Nominations Committee, Association of Research Libraries (ARL), 2016.

Steering Committee, Scholarly Publishing and Academic Resources Coalition (SPARC), 2016 – 2017.

"Excellence in Library Services," Chair, Review Team, University of Hong Kong, Hong Kong, August 24-27, 2015.

Chair, Management Advisory Board, 2015-2017; Member, Scientific Advisory Board, arXiv, Cornell University, 1/1/2013 – present.

Advisory Board for the Wayne State University School of Library and Information Science, July 2012 – present.

Advisory Board for Microsoft Academic Search, 2012 – 2015. Redmond, WA.

Transforming Research Libraries, a Strategic Direction Steering Committee of the Association of Research Libraries (ARL), 2012-2015.

Science and Technology section, representing ARL, International Federation of Library Associations (IFLA), Chair, 2013 – 2017; Member, 2011 to present.

Member of University of Pretoria, South Africa, Library Review Committee. August 2013.

Co-chair, Local Arrangements Planning Committee for 2013 Conference, Association of College and Research Libraries (ACRL), a division of the American Library Association (ALA).

Association of Research Libraries Leadership & Career Development Program Mentor, 2011-2017.

e-Science Task Force, Association of Research Libraries. July 2006 – present. Chair, October 2011 – October 2012.

Board of Directors, International Association of Technological University Libraries (IATUL). January 2008 – December 2014.

Midwest Collaborative for Library Services (MCLS); Board Member, October 2010 – December 2012.

Chair, Library Directors, Committee on Institutional Cooperation (CIC), July 2010 – June 2012.

Board of Directors, Association of Research Libraries (ARL); October 2008 – October 2011.

Scholarly Communication Steering Committee, Association of Research Libraries (ARL)

2008-2011.

Editorial Board, *College and Research Libraries*, Association of College and Research Libraries, American Library Association. January 2008 – December 2014.

Chair, Organizing Committee for IATUL Conference 2010, June 21-24, 2010, Purdue University, West Lafayette, Indiana/Chicago, Illinois.

Conference Planning Committee for National Conference of the Association of College and Research Libraries, 2009, Seattle, Washington.

Research Committee, Association of College and Research Libraries, ACRL, division of ALA. 2002-2007, chair, 2005-2007.

Association of Research Libraries, Search and Screen Committee, Executive Director. March – January 2008.

Center for Research Libraries, Board of Directors. April 2006 – April 2012.

Academic Libraries of Indiana, Board of Directors, 2004 – present. Vice-president, 2005-2007. President, 2007- 2009.

ALA Representative to the International Federation of Library Associations (IFLA), Marketing and Management (M&M) Section, initial term 2003-2007, re-appointed for second term, 2007-2011.

Invited to represent Research Libraries at the ACRL/3M Wonewok Retreat to assess Marketing of Academic Libraries, October 2002.

Hugh A. Atkinson Award Committee, LAMA Representative, ALA, 2001-2005.

Program Committee, Library Administrators and Management Association (LAMA), a division of ALA. 1996-2001.

ACRL, Standards and Accreditation Committee, a division of ALA. Liaison to RBMS Section of ACRL. 1997-2002.

Elected to the Executive Committee of LAMA, LOMS, a division of the American Library Association, 1998-2000. Nominated as Chair/Elect for 2003 – 2005.

Columbia University Press Advisory Committee. 1996 - 2000.

LITA/LAMA Conference Evaluation Committee, Pittsburgh, Pennsylvania, October 1996.

"New Learning Communities," Coalition for Networked Information, Indianapolis. November 19-21, 1995. Facilitator for invitational, national conference committed to developing collaborative learning and teaching techniques, involving librarians.

Planning Committee-Evaluation. LITA/LAMA 1996 Conference, Pittsburgh. This first conference, to be held jointly between two divisions of ALA, will focus on new technologies within libraries.

Indiana Cooperative Library Services Authority (InCoLSA), elected to Executive Committee, April 1991, served as President in 1993-94. InCoLSA is a statewide network of academic, public, school and special libraries that supports library cooperation for cataloging, interlibrary loan, collection development and application of new technologies.

Governor's Conference on Libraries and Information Services. Served on Planning Committee, Academic Libraries Representative, appointed by the Governor to represent academic libraries in Indiana, Chair, Finance Committee, April 1989-July 1991.

Indiana Library Endowment Foundation Board, 1984-92. Charter Member, 1984, President, 1988-1992. 2004-2005.

University Service: (Summary)

Served on search and screen committees for senior positions including chancellor, dean and directors; most recently I have been asked to serve on the search committee for the provost of Purdue University. At MIT service included the Library Council & appointment to the Administrative Council by President Vest, 2001-2003 & Member of the Faculty Committee on the Library System. At Purdue appointed by the President to the Search Committee for the Provost, October 2007 to May 2008; member of the Capital Projects Committee, and IT Operational Oversight Committee as senior academic dean, 2008-2014;

Global Council, Global Policy Institute, 2012 – 2016.

Academic Program Excellence and Rankings (APER) project team, 2014.

Representative of the Academic Deans on the Re-engineering Business Operations, Purdue University, 2016 –

Academic Deans Council chaired by Provost – 2004 – 2017.

University Promotion and Tenure Committee – 2006 – 2017.

"Outstanding Team Award, Electronic Reserve Project," served as Chair, recognition awarded by the President of Villanova University to one team who made an outstanding contribution to the operations of the University, selected by a committee of administrators, faculty, and staff. Awarded September 9, 1999.

Nominated for the IUSB Lundquist Award, 1995 & 1996. The Lundquist award is given to faculty who have "exhibited excellence in teaching, scholarly or artistic achievement, and diversified relevant service..."

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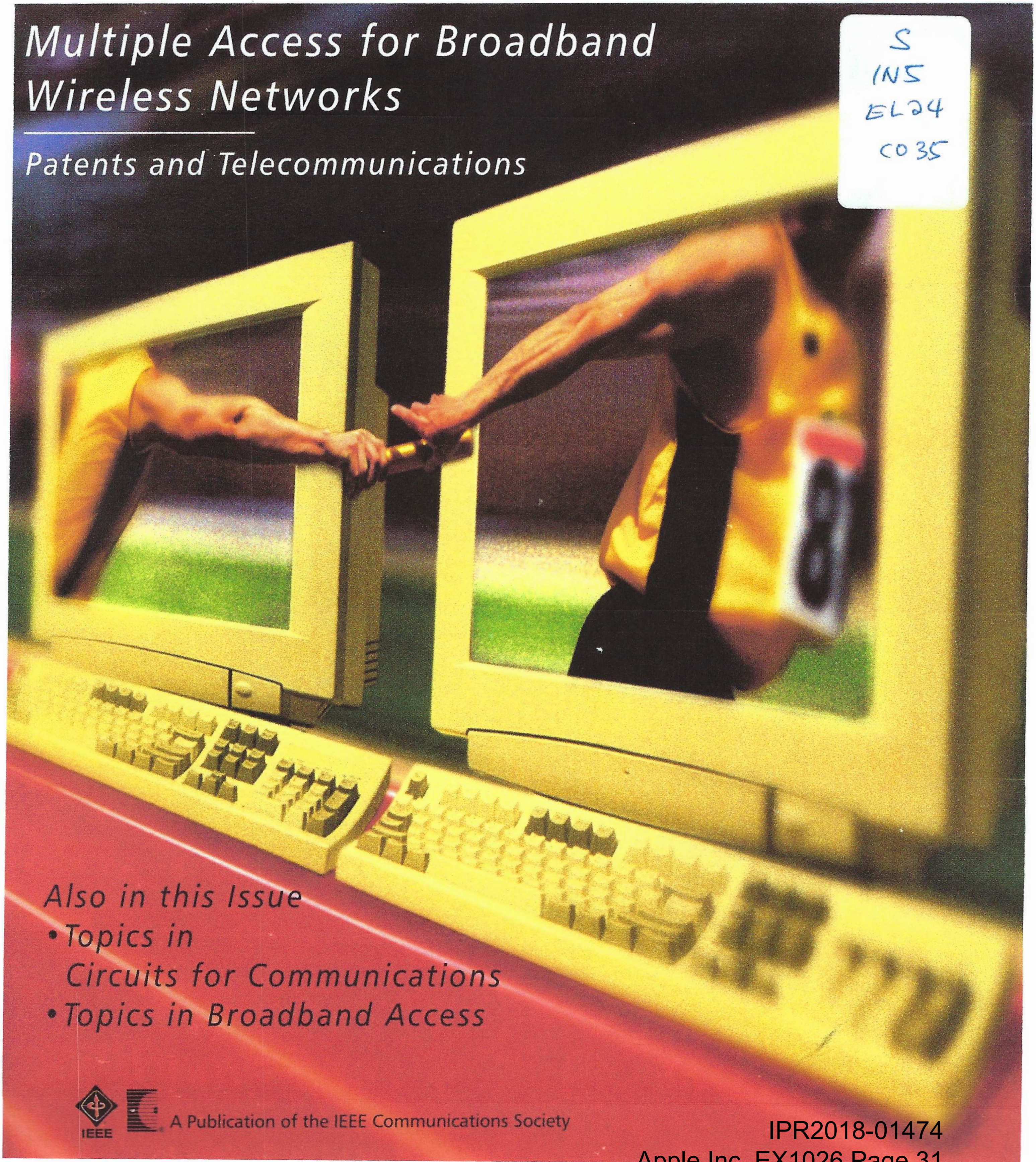

Multiple Access for Broadband Wireless Networks

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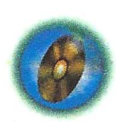

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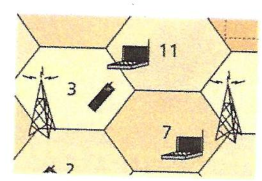
Multiple Access for Broadband Wireless Networks

Guest Editor: Benny Bing



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PATENTS AND TELECOMMUNICATIONS

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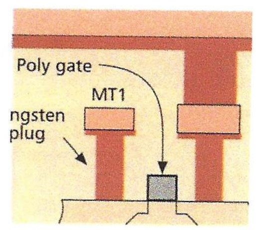

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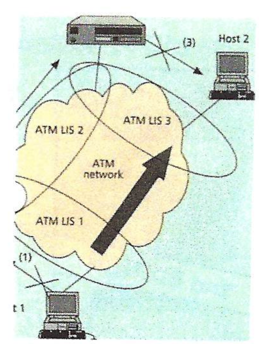

CDMA/HDR: A Bandwidth-Efficient High-Speed Wireless Data Service for Nomadic Users

Paul Bender, Peter Black, Matthew Grob, Roberto Padovani, Nagabhushana Sindhushayana, and Andrew Viterbi, QUALCOMM, Incorporated

ABSTRACT

This article presents an approach to providing very high-data-rate downstream Internet access by nomadic users within the current CDMA physical layer architecture. Means for considerably increasing throughput by optimizing packet data protocols and by other network and coding techniques are presented and supported by simulations and laboratory measurements. The network architecture, based on Internet protocols adapted to the mobile environment, is described, followed by a brief discussion of economic considerations in comparison to cable and DSL services.

INTRODUCTION

The rapid growth and nearly universal coverage of industrialized nations and regions by digital wireless telephony gives rise to an increasing demand for data services as well. While current offerings are for data rates equivalent to those provided by wireline modems a decade or more ago, the gap is closing. Standards are already approved and chip sets are available for providing data rates above 64 kb/s within this calendar year (and century). Just beyond this horizon, however, service providers are already planning for wireless data rates above 2 Mb/s, approaching those of wireline, digital subscriber line (DSL), and cable. Whether such a wireless service can be made technically and economically competitive with wireline and cable is not the main issue, although we shall address this briefly in the last section. What will drive such a service is the demand for rapid low-latency availability of Internet access to nomadic users. In the next section we describe the characteristics and perceived needs of this user class. We then proceed to explore the characteristics of data requirements for speed and latency, after which we present a technical system solution tailored to these requirements and the characteristics of a specific implementation as an evolution of existing CDMA base station and subscriber terminal architectures. In the final section we briefly discuss the economics of such a system deployment.

CHARACTERISTICS OF NOMADIC USER DATA DEMAND

In business and the professions, the individual is often absent from her or his normal workplace. To continue to be productive on the road, both in transit and at business or professional meetings, connectivity to data at one's principal workplace and more broadly to other databases accessible through the Web is essential. Generally, members of this nomadic user class demand the same data service normally available in their home base. Often cited examples of the nature of such services are e-mail retrieval, Web browsing, ordering airline tickets, hotel reservations, obtaining stock quotes, and report retrieval, in such locations as airport lounges, hotel rooms, and meeting places, in each case without recourse to the limited or interface unfriendly facilities available in such places. In fact, one need not necessarily look beyond corporate boundaries; professional employees often spend nearly as much time in company conference rooms as in their own offices, and rarely are such rooms equipped with the number of ports needed to connect the majority of participants' laptops.[1]

The nature of such data traffic is decidedly asymmetric. A much higher forward (or downlink) rate is required from the access point (base station) than that generated by the access terminal (user terminal) in the reverse (uplink) direction. Furthermore, just as does the fixed user, the nomadic user expects a response to her or his request which does not suffer from excessive latency. Our goal is to satisfy these needs with an evolutional approach which minimizes the time and cost for providing such capabilities in existing cellular infrastructure and with terminals that differ only at digital baseband from existing cellular and personal communications systems (PCS) handsets.

[1] *The obvious alternative of private campus wireless systems will be discussed in the last section.*

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THE TECHNICAL CHALLENGE

Little information has been gathered on the exigencies of nomadic users and the networks to serve them, simply because, with the exception of a very small percentage of low-speed data service, such networks have not existed. On the other hand, with digital cellular networks in place for nearly a decade and with large numbers of mobile users served for several years, a great deal is known about the characteristics of digital wireless networks and their mobile users. A major step in the perfection of digital cellular technology was the development and standardization of code-division multiple access (CDMA) wireless systems and their adoption by the majority of North American, Korean, and Japanese carriers and manufacturers. Having proven its superiority to other access techniques, it is now being imitated (sometimes in a modified form) by most of the carriers and manufacturers who were the initial holdouts and skeptics of its viability.

CDMA was designed for efficient reverse (uplink) and forward (downlink) operations. It was initially widely believed that the reverse direction in which multiple users access each base station, hence representing multiple sources of interference with one another, would be the capacity limiting (or bottleneck) direction. This assumption turned out to be incorrect; the forward (downlink) was the initial bottleneck for three principal reasons:

- Interference on the reverse link enjoys the advantage of the law of large numbers, whereby the cumulative interference from multiple low-power transmitters tends to be statistically stable. The forward link, on the other hand, suffers interference from a small number of other high-power base stations. This becomes particularly serious at the vertices of the (imaginary) cellular hexagon where the transmitting base station and two other interfering base stations are equidistant from the intended user. This situation is relieved by soft handoff, where two or more base stations transmit to the user simultaneously.
- But soft handoff, while greatly diminishing interference, which itself increases capacity, still overall diminishes the forward link[2] capacity because an additional CDMA carrier must be assigned in the newly added base station. Depending on the region of (or criterion for) soft handoff, this can cause greater or lesser reduction.
- While on the reverse link, fast and accurate power control of multiple users is evidently critical to operation and capacity realization, it was initially felt in producing the first CDMA standard, cdmaOne (IS-95-A [1]), that forward link power control could be much slower. This turned out to reduce forward link capacity.

The second and third limiting causes have been eliminated or considerably diminished in the evolutionary revisions of cdmaOne (IS-95-B and CDMA2000). Fast power control is now implemented in the forward link, and the region of (criterion for) soft handoff has been diminished. The first cause (sometimes called the "law of small numbers"), remains, however. These improvements have brought the forward (downlink) capacity to parity with the reverse (uplink) capacity. But for high-speed data, such as downloading from the Internet, this is *not enough*. The downlink demand is likely to be several times greater than the uplink. The rest of this article deals with new approaches which will further increase the downlink capacity by a factor of three to four for data applications only.[3]

THE TECHNICAL APPROACH TO HIGH-SPEED DATA

Most data applications differ fundamentally from speech requirements in two respects already noted, traffic asymmetry and tolerance to latency. Two-way conversational speech requires strict adherence to symmetry; also, latencies above 100 ms (which corresponds to about 1 kb of data for most speech vocoders) are intolerable. For high-speed data downlinked at 1 Mb/s, for example, 100 ms represents 100 kb or 12.5 kbytes; furthermore, latencies of 10 s are hardly noticeable, and this corresponds to a record of 1.25 Mbytes. Thus, smoothing over a variety of conditions, which is always advantageous for capacity, is easily accomplished.

All communication systems, wired as well as wireless, are greatly improved by a combination of techniques based on three principles:

- Channel measurement
- Channel control
- Interference suppression and mitigation

Our approach employs all three. First, on the basis of the received common pilot from each access point (or base station), each access terminal (subscriber terminal) can measure the received signal-to-noise-plus-interference ratio (SNR). The data rate which can be supported to each user is proportional to its received SNR. This may change continuously, especially for mobile users. Thus, over each user's reverse (uplink) channel, the SNR or equivalently the supportable data rate value is transmitted to the base station. In fact, since typically two or more base stations may be simultaneously tracked, the user indicates the highest among its received SNRs and the identity of the base station from which it is receiving it, and this may need to be repeated frequently (possibly every slot[4]). In this way the downlink channel is controlled as well as measured. Furthermore, by selecting only the best base station, in terms of SNR, to transmit to the user, interference to users of other base stations is reduced. Additionally, since data can tolerate considerably more delay than voice, error-correcting coding techniques which involve greater delay, specifically turbo codes, can be employed which will operate well at lower E_b/N_0, and hence lower SNR and higher interference levels.

Next, we show how unequal latency, for users of disparate SNR levels, can be used to increase throughput. Suppose we can separate users into N classes according to their SNR levels, and corresponding instantaneous rate levels supportable. Thus, user class n can receive slots at rate R_n b/s, where $n = 1.2..N$, and suppose the relative frequency of user packets of class n is P_n.

All communication systems, wired as well as wireless, are greatly improved by a combination of techniques based on three principles: channel measurement, channel control, and interference suppression and mitigation Our approach employs all three.

[2] *Although not the capacity of the reverse link, which soft handoff actually increases.*

[3] *Clearly voice is fundamentally a symmetric service, with stricter latency requirements, as we shall note below.*

[4] *In speech-oriented CDMA, voice frames are 20 ms long. In the next section, we shall establish corresponding lengths for data, which will be called slots. Multiplying R_{av} of (1) by slots per second yields throughput in bits per second.*

Data rate (kb/s)	Packet length (bytes)	FEC rate (b/sym)	Modulation
38.4	128	1/4	QPSK
76.8	128	1/4	QPSK
102.6	128	1/4	QPSK
153.6	128	1/4	QPSK
204.8	128	1/4	QPSK
307.2	128	1/4	QPSK
614.4	128	1/4	QPSK
921.6	192	3/8	QPSK
1228.8	256	1/2	QPSK
1843.2	384	1/2	8PSK
2457.6	512	1/2	16QAM

Table 1. *Various data rates.*

Suppose slots are assigned one at a time successively to each user class. Then the average rate, which we define as throughput, is

$$R_{av} = \sum_{n=1}^{N} P_n R_n \ \text{b/s}. \qquad (1)$$

This, of course, means that lower-data-rate (and SNR) users will have proportionately higher latency. For if B bits are to be transmitted altogether for each class, the number of slots (and hence time) required for user class n will be B/R_n, and hence the latency L_n is inversely proportional to R_n.

Suppose, on the other hand, that we require all users to have essentially the same latency[5] irrespective of the R_n they can support. Then as each user class is served, it will be allocated a number of slots inversely proportional to its rate. Let F_n be the number of slots allocated to class n, where $F_n = k/R_n$, k being a constant. In this case, the average rate or throughput is

$$R'_{av} = \frac{\sum_{n=1}^{N} P_n R_n F_n}{\sum_{n=1}^{N} P_n F_n} = \frac{1}{\sum_{n=1}^{N} P_n / R_n} \ \text{b/s}. \qquad (2)$$

In this case, however, the latency of all user classes will be the same (assuming the total number of bits K to be large and thus ignoring edge effects).

To assess the cost in throughput for equalizing latency, consider the extreme case of only two user classes, each equally probable ($P_1 = P_2 = 1/2$) but capable of supporting very disparate rates $R_1 = 16$ kb/s, $R_2 = 64R_1 = 1{,}024$ kb/s. Then in the first case, $R_{av} = 520$ kb/s. but $L_1/L_2 = 64$. In the second case, $L_1 = L_2$, but $R'_{av} = 31.51$ kb/s.

To see that there is a more rational allocation which is less "unfair" than a latency ratio of 64, and still achieves a better throughput than R'_{av}, consider a compromise which guarantees that the highest latency is no more than, for example, 8 times the lowest latency. Then in the second case, we would assign 8 slots to class 1 for every slot assigned to class 2. The result would be $L_1/L_2 = 8$ as required and

$$R_{av}'' = (8FP_1R_1 + FP_2R_2)/(FP_1 + FP_2) = 128 \text{ kb/s}.$$

For the general case of N classes and latency ratio L_{max}/L_{min}, it can be shown that the maximum achievable throughput, denoted by C, is

$$C = \frac{\sum_{n=1}^{n_o} P_n + \sum_{n=n_o+1}^{N} P_n (L_{min}/L_{max})}{\sum_{n=1}^{n_o} P_n/R_n + \sum_{n=n_o+1}^{N} (P_n/R_n)(L_{min}/L_{max})} \ \text{b/s}, \qquad (3)$$

where $R_1 < R_2 \ldots R_N$ and n_o is such that $R_n \le C$ for all $n \le n_o$, while $R_n > C$ for all $n > n_o$.

Surprisingly, with this maximizing strategy, each user's latency is either L_{max} (for those for which $R_n < C$) or L_{min} (for those for which $R_n > C$). To determine the maximum throughput it is necessary to have a histogram of the achievable rates for users of the wireless network in question. This will be discussed in the next section. Also, as we shall find there, practical numerology considerations may require us to deviate from this strict bimodal latency allocation, although the ratio L_{max}/L_{min} will remain as the principal constraint.

Implementation of High-Data-Rate Code-Division Multiple Access

In the last section we discussed the key factors and parameters of a wireless system designed to optimize the transport of packet data. In the following we will describe such a system design, beginning first with a description of the air interface, to continue in the next section with a description of the network architecture. The design leverages in many ways the lessons learned from the development and operation of CDMA IS-95 networks, but makes no compromises in optimizing the air interface for data services. Furthermore, a compelling economic argument can be made for a design that can reuse large portions (to be exact, all but the baseband signal processing elements) of components and designs already implemented in IS-95 products, both in the access terminals and access points (APs).

Due to the highly asymmetric nature of the service offered, we will focus most of our attention on the downlink. In the IS-95 downlink, a multitude of low-data-rate channels are multiplexed together (with transmissions made orthogonal in the code domain) and share the available base station transmitted power with some form of power control. This is an optimal choice for many low-rate channels sharing a common bandwidth. The situation becomes less optimal when a low number of high-rate users share the channel. The inefficiencies increase further when the same bandwidth is shared between low-rate voice and high-rate data users, since their requirements are vastly different, as discussed previously. It should be noted that

[5] *This is the case for voice. The only difference is that in speech, transmitter power levels are controlled to equalize received power, while here time, in terms of frames, is controlled to equalize energies.*

increasing the bandwidth available for transmission cannot help in this regard if the data rate of the users is increased proportionally as well.

Therefore, a first fundamental design choice is to separate the services, that is, low-rate data (voice being the primary service in this category) from high-rate data services, by using possibly adjacent but nonoverlapping spectrum allocations. To summarize, a better system is one that uses an IS-95 or cdma2000-1X RF carrier to carry voice and a separate high-data-rate (HDR) RF carrier to deliver high-rate packet bursts.

With a dedicated RF carrier, the HDR downlink takes on a different form than that of the IS-95 designs. As shown in Fig. 1, the downlink packet transmissions are time multiplexed and transmitted at the full power available to the AP, but with data rates and slot lengths that vary according to the user channel conditions. Furthermore, when users' queues are empty, the only transmissions from the AP are those of short pilot bursts and periodic transmissions of control information, effectively eliminating interference from idling sectors.

The pilot bursts provide the access terminals with means to accurately and rapidly estimate the channel conditions. Among other parameters, the access terminal estimates the received E_c/N_t of all resolvable multipath components and forms a prediction of the effective received[6] SNR. The value of the SNR is then mapped to a value representing the maximum data rate such a SNR can support for a given level of error performance. This channel state information, in the form of a data rate request, is then fed back to the AP via the reverse link data rate request channel (DRC) and updated as fast as every 1.67 ms, as shown in Fig. 2. The reverse link data request is a 4-bit value that maps the predicted SNR into one of the data rate modes of Table 1. In addition, the access terminal requests transmission from only one sector (that with the highest received SNR) among those comprising the *active set*. Here the definition of active set is identical to that for IS-95 systems, but unlike IS-95, only one sector transmits to any specific access terminal at any given time.

The main coding and modulation parameters are summarized in Table 1.

The forward error correcting (FEC) scheme employs serial concatenated coding and iterative decoding, with puncturing for some of the higher code rates [2].

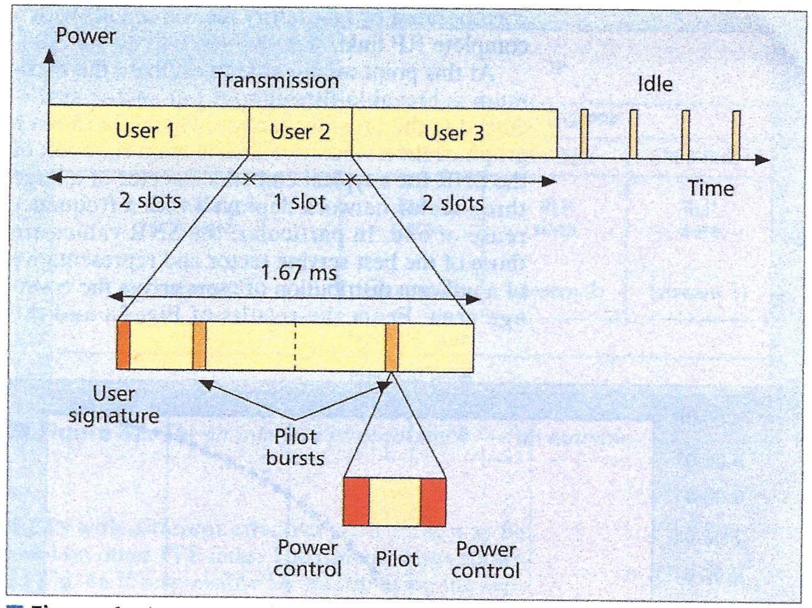

Figure 1. *An access point transmission diagram.*

Following the encoder, these traditional signal processing steps are applied: symbol repetition is performed on the lower-data-rate modes; scrambling, channel interleaving, and the appropriate modulation is applied to obtain a constant modulation rate of 1.2288 MHz for all modes. The in-phase and quadrature channels are then each demultiplexed into 16 streams, each at 76.8 kHz, and 16-ary orthogonal covers are applied to each stream. The resulting signal, obtained by adding the 16 data streams, is then spread by quadrature pseudonoise (PN) sequences, bandlimited and upconverted. The resulting RF signal has the same characteristics as an IS-95 signal, thus allowing the reuse of all analog and RF designs developed for IS-95 base stations, including the power amplifiers, and the receiver designs for subscriber terminals.

Table 2 summarizes the SNR required to achieve a 1 percent packet error rate (PER).

Note that at the lower rates this corresponds to $E_b/N_0 \approx 2.5$ dB, a result of using iterative decoding techniques on serial concatenated codes, while for the two highest rates, E_b/N_0 increases considerably because 8-phase shift keying (PSK) modulation and 16-quadrature amplitude modulation (QAM) are employed. These were obtained both by bit-exact simulation and

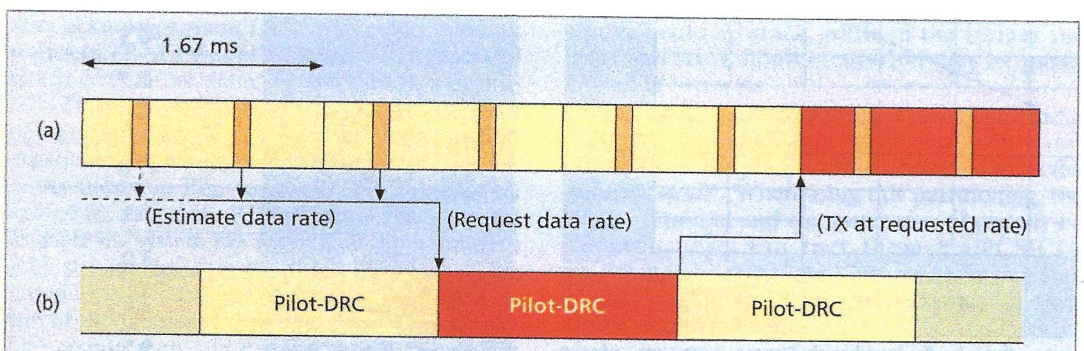

Figure 2. *A channel estimation and data request channel timing diagram: a) access terminal receive; b) access terminal transmit.*

[6] E_c *represents the received signal energy density and* N_t *represents the total nonorthogonal single sided noise density.* N_t *comprises intercell interference, thermal noise, and possibly nonorthogonal intracell interference.*

corroborated by laboratory measurements with a complete RF link.

At this point we are able to estimate the maximum achievable throughput per sector as discussed in the previous section. Figure 3a shows a graph of the cumulative distribution function of the SNR for a typical embedded sector of a large three-sector network deployed with a frequency reuse of one. In particular, the SNR values are those of the best serving sector and representative of a uniform distribution of users across the coverage area. From the results of Fig. 3a and the knowledge of the SNR required to support a given data rate (Table 1), it is straightforward to derive the histogram of data rates achievable in such an embedded sector. The result is shown in Fig. 3b where the SNRs used in the calculation are those of Table 1 with an additional 2 dB of margin to account for various losses. Finally, Fig. 3c shows the realized throughput per sector per 1.25 MHz of bandwidth versus the parameter L_{max}/L_{min}. Note that the throughput is doubled for a latency ratio $L_{max}/L_{min} = 8$.

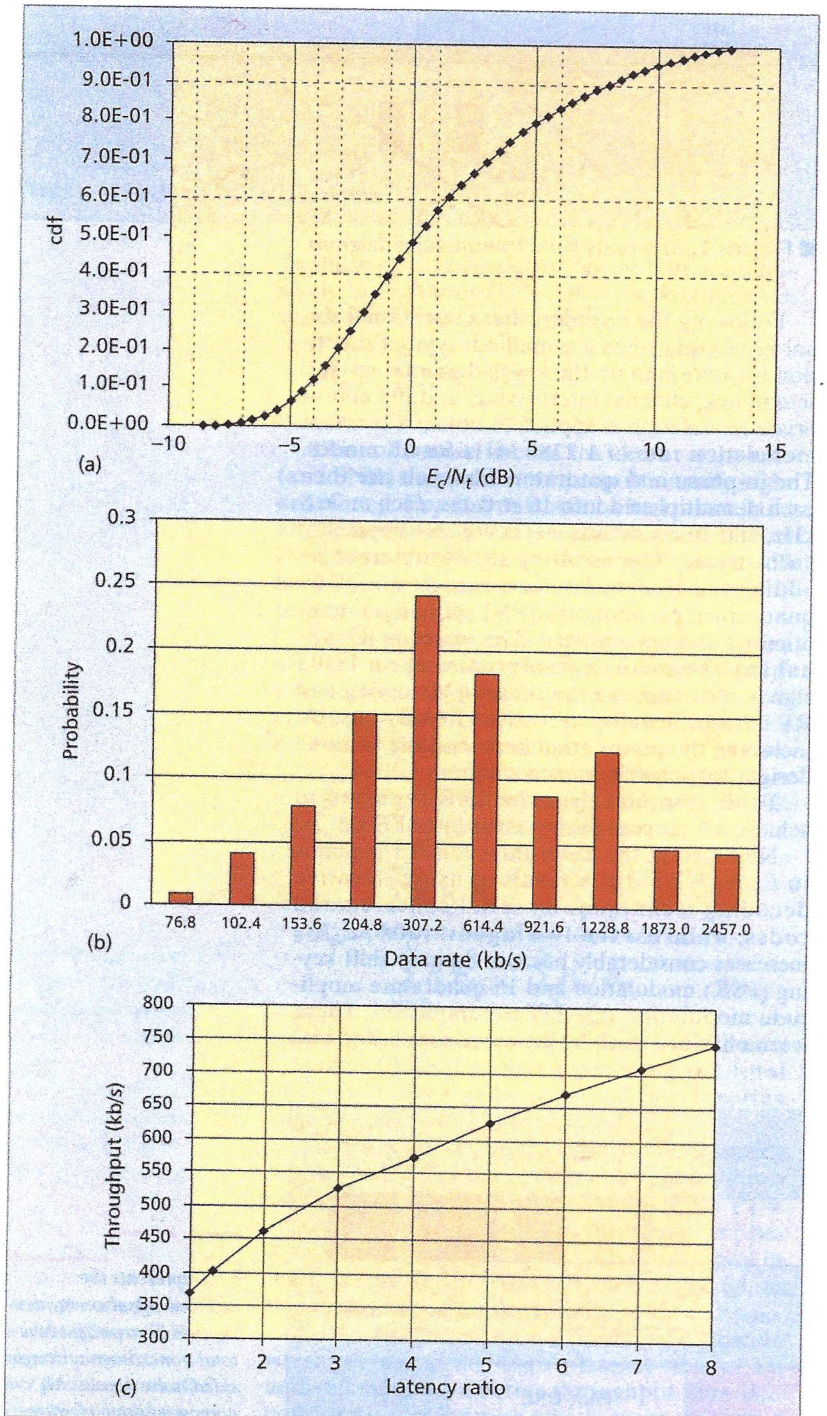

Figure 3. *a)* E_c/N_t *distribution for a typical embedded sector in a three-sector network with universal frequency reuse in each cell; b) data rate histogram; c) sector throughput vs. latency ratio* L_{max}/L_{min}.

Network Architecture

Since the radio link has been designed to provide efficient access to packet data networks, it is natural to turn to the most ubiquitous packet data network — the Internet — when selecting the network architecture. Adopting Internet protocols in the communication between the access terminal and the access network allows users to access the widest variety of information and services, including e-mail, private intranets, and the World Wide Web. Furthermore, the selection of Internet protocols in the design of the access network allows the access network equipment to take advantage of the ever decreasing costs and increasing performance of Internet equipment.

First, we examine the communication link between the access terminal and the access network. Figure 4a shows the protocol stack used in such a link.

In order to carry traffic between the user and the network, we need to select a network-layer protocol. We chose the Internet Protocol (IP) [3] because it is the network-layer protocol of the Internet. The Internet carries its network-layer protocol over a variety of transports. For example, asynchronous transfer mode (ATM) often carries Internet traffic on the Internet backbone, Ethernet often carries Internet traffic on local area networks (LANs), and the Point-to-Point Protocol (PPP) [4] often carries Internet traffic over dialup connections. We chose PPP for the following reasons. First, PPP is widely supported. Moreover, PPP allows the transport of a variety of network-layer protocols, supports methods for

Data rate (kb/s)	E_c/N_t (dB)
38.4	−12.5
76.8	−9.5
102.6	−8.5
153.6	−6.5
204.8	−5.7
307.2	−4.0
614.4	−1.0
921.6	1.3
1228.8	3.0
1843.2	7.2
2457.6	9.5

Table 2. *SNR for a 1 percent packet error rate.*

differing quality of service (QoS) requirements, and also supports methods for authentication. Lastly, PPP has low overhead, an important feature for a wireless transport.

It is well known that the Internet carries different types of traffic with different QoS requirements. Some traffic, such as Transmission Control Protocol (TCP) [5] traffic, tends to be more sensitive to errors and less sensitive to delay. Other traffic, such as Real-Time Transport Protocol (RTP) [6] traffic, tends to be more sensitive to delay and less sensitive to errors. In order to support these differing QoS constraints over a single physical link between two Internet nodes (e.g., routers or personal computers), many nodes insert traffic with different QoS requirements into different queues. Then, by servicing the queues based on the different QoS requirements, the node attempts to provide the QoS desired by the different types of traffic. For PPP sessions, multiple queues over a single physical link are supported using the PPP Multilink Protocol (MP) [7]. In this configuration each queue is carried by a different PPP link. This feature allows PPP to support differing QoS requirements. For instance, in the example shown in Fig. 4a the system has negotiated three PPP links.

Since radio link bandwidth is a limited resource, we should consider protocol overhead when choosing a protocol that will be carried over the radio link. PPP has been designed to minimize its own protocol overhead. In addition, it supports the compression of network-layer protocol headers such as TCP and IP/UDP/RTP header compression, further reducing the overhead of carrying user traffic over radio links.

It is typical to operate HDR with a received signal-to-noise ratio that results in a physical-layer PER of approximately 1 percent. This error rate is significantly higher than the error rate seen on most wireline networks. Since most network protocols and most network applications were designed assuming wireline error rates, the wireless link error rate needs to be reduced. The most straightforward method of reducing the error rate is for access terminals to operate at a higher signal-to-noise ratio regime. However, the increase in the signal-to-noise ratio required to reach wireline error rates results is a substantial decrease in overall throughput. A more efficient method for decreasing the error rate of the wireless link is obtained by implementing a form of automatic repeat request (ARQ). HDR implements a negative acknowledgment (NACK)-based radio link protocol (RLP) whereby incorrectly received blocks of data are detected and then retransmitted. This allows PPP and the higher layers to operate at an error rate regime similar to that experienced in wireline networks.

As shown in Fig. 4a, each PPP link may be carried by a separate RLP stream. In this specific example the system has negotiated three separate RLP streams to carry the three PPP links. This introduces the flexibility of allowing for finer control of the QoS. For instance, depending on the QoS requirement, different transmit scheduling policies with differing priorities may be implemented on some PPP streams. Additionally,

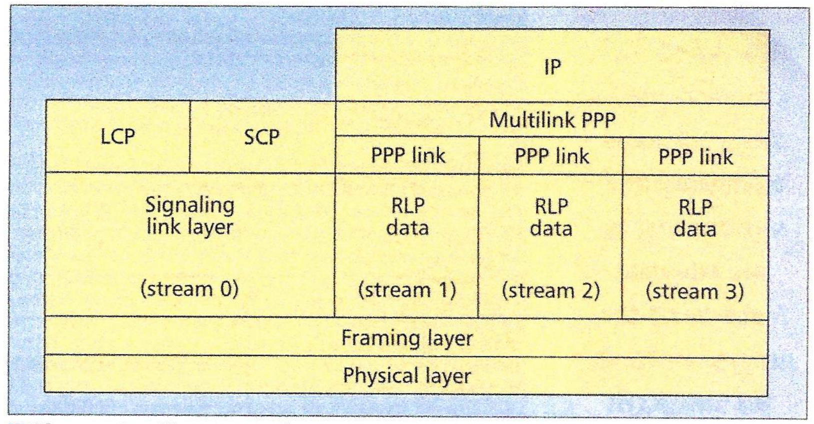

Figure 4a. *The air interface protocol stack — an example.*

RLPs with different effective error rates may be used on other PPP links. The framing layer shown in Fig. 4a is responsible for multiplexing the separate RLP streams into one physical layer.

In addition to user traffic, the HDR radio link must support the transport of signaling messages. The model for the transport of signaling streams is based on PPP. Signaling is partitioned into two basic types: the Link Control Protocol (LCP) and Stream Control Protocol (SCP). Similar to the PPP LCP, the LCP is used to negotiate radio link protocols and options at the start of the session and to control the radio link during the session. For example, the LCP is used at the start of the session to negotiate the link layer authentication type that will be used for the duration of the session. Similar to the PPP Network Control Protocol (NCP), the SCP is used to carry stream-specific signaling messages. For example, SCP is used to transmit the RLP NACKs upon detection of missing RLP data.

In the remainder of this section we discuss in which elements of the network the various layers of the protocols may be implemented. First we will describe the implementation on the user side of the air interface, to be followed by a brief description of the network side.

On the user side of the air interface reside two basic functional elements: the access terminal and the computer. These elements may reside in two devices, as in the case of a wireless HDR modem connected to a portable computer, or may be combined into a single device such as a wireless personal digital assistant (PDA). In the latter case, the device must implement the entire protocol stack, while in the former the protocol stack implementation may be partitioned in two ways.

In the first partitioning method, the access terminal implements the entire protocol stack. This partitioning is sometimes referred to as the *network model*. When using this partitioning, the access terminal and computer may physically be connected over Ethernet, through a PCMCIA interface, or over the Universal Serial Bus (USB). Figure 4b shows the layering endpoints of the network model.

In the second partitioning method, the access terminal implements the entire protocol stack with the exception of PPP and everything above PPP, *A first fundamental design choice is to separate the services, that is, low-rate data (voice being the primary service in this category) from high-rate data services, by using possibly adjacent but non-overlapping spectrum allocations.*

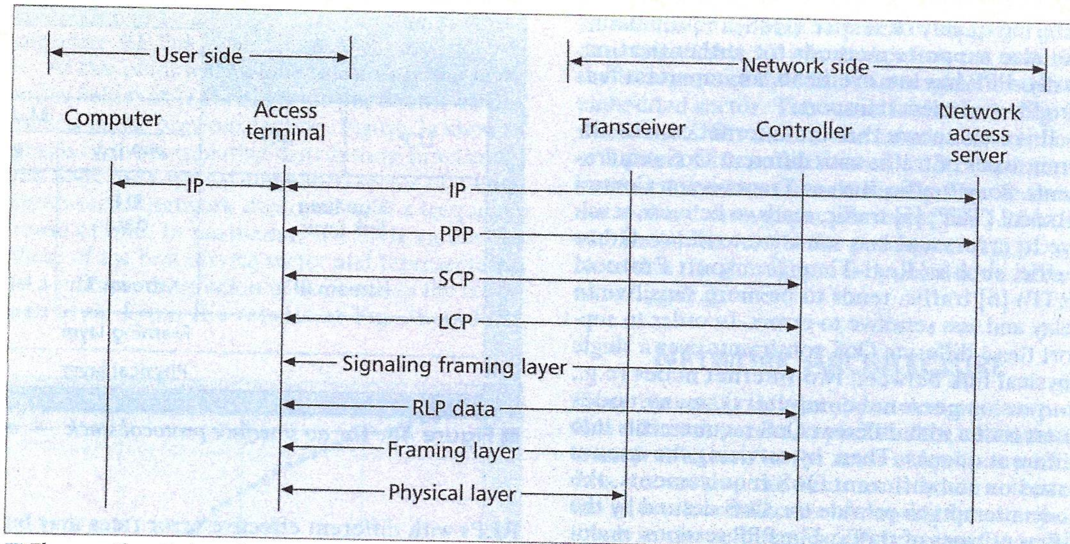

Figure 4b. *Air interface protocol endpoints — the network model.*

while the computer implements PPP and all protocols above PPP. This partitioning is sometimes referred to as the *relay model*. In the relay model, the access terminal and computer may be physically connected via RS-232 or USB. Figure 4c shows the layering endpoints of the relay model.

The network side of the air interface is modeled on the traditional Internet network access server (NAS) [8]. There are three basic functional elements: the transceiver, the controller, and the NAS. The transceiver implements the physical layer. The controller implements the framing layer, the RLP data layer, the signaling link layer, and all layers above the signaling link layer. The three functional blocks communicate over IP using open interfaces. The NAS implements the PPP layer and all layers above PPP. Figures 4b and 4c show the layering endpoints for the partitioning.

In our design of the access network, the access point implements the transceiver, the controller, and the NAS functional elements. The network interface implements the protocols and interfaces needed to connect the access point to an IP network and a backhaul network. Since the transceiver, controller, and NAS communicate over IP using open interfaces, there is no strict requirement for all the elements to be located in the access point. For example, in a more traditional cellular implementation, one might choose to centralize the controller and the NAS.

Only the transceiver and controller are specific to the radio link. The NAS and network interface are standard equipment used by today's Internet service providers (ISPs). By using an interface such as the widely supported Layer Two Tunneling Protocol (L2TP) between the NAS and the modem pool controller, it is possible to use this standard ISP equipment for many applications.

With the exception of other access points, the access point communicates with all elements in the access network using widely deployed Internet protocols. In addition, the access point transports all traffic using IP. Therefore, with the exception of the access point itself, all equipment in an access network is readily available Internet equipment.

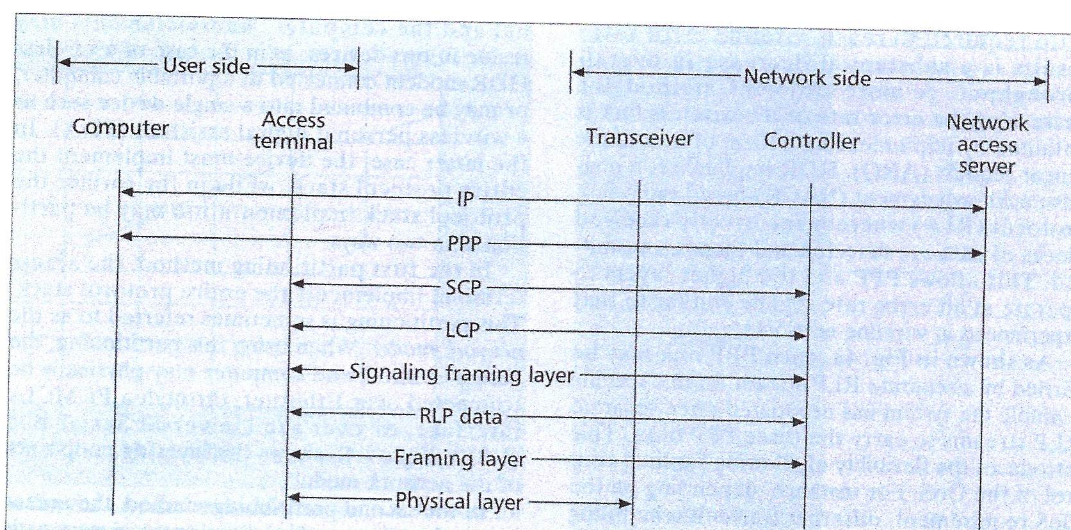

Figure 4c. *Air interface protocol endpoints — the relay model.*

Economics and Tariff Considerations

We consider finally the critical issue of the value of the service and how to establish tariffs. For truly nomadic users, constant travelers, people who prefer to work on their patio, at the beach or on the slopes, and so on, the service is most valuable and cannot be compared with high-speed wireline services provided by DSL or cable modems. At the other extreme for strictly fixed users, whose offices or homes are connected by fiber or wireline/cable services, the economics usually favor the latter. Suppose, however, that a carrier must decide between a wireline/cable high-speed solution or the wireless approach of this article. Here capital expenditures and possible tariff considerations dominate. The problem for wireless is that established wireline services have already conditioned users to expect a flat monthly rate essentially independent of the amount of service. The idealized economic model for digital packet-based wireless, practical considerations aside, will be to charge for usage on a packet basis.[7]

Most likely, however, most users will constitute a population of varying degrees of nomadicity, but even the occasional nomad will grow to depend on the flexibility and continuity provided by the "anywhere, anytime" nature of wireless connectivity. If this indeed turns out to be the case, even private networks (LANs) may be supplanted by wireless HDR usage. Economies of scale would seem to favor the HDR microcell located in or near a corporate campus over the private network. In fact, the best architecture for the latter may coincide with that of the former. Were this to occur, fiber, wire, and cable pipes may be relegated to the backbone and to the occasional supercomputer node, with the last kilometer or less becoming universally wireless for the majority of users.

Most users will likely constitute a population of varying degrees of nomadicity, but even the occasional nomads will grow to depend on the flexibility and continuity provided by the "anywhere, anytime" nature of wireless connectivity.

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Biography

PAUL BENDER is vice president of technology for Corporate Research and Development of QUALCOMM Incorporated. He received his Ph.D. in electrical engineering in 1992 with an emphasis on communications theory and systems at the University of California, San Diego (UCSD). He joined QUALCOMM in August 1992 and has contributed his expertise to the development of innovative CDMA digital communications at QUALCOMM. His responsibilities have included building the system test team and leading the system engineering team for the (IS-95) cellular and PCS infrastructure. He is currently involved in the development of QUALCOMM's High Data Rate (HDR) technology. Prior to joining QUALCOMM, he conducted research in signal processing for digital recording at UCSD's Center for Magnetic Recording Research. In addition, he assisted students in designing and debugging basic analog circuits for the Electrical and Computing Engineering Department at UCSD.

PETER J. BLACK is vice president of technology for Corporate Research and Development, of QUALCOMM Incorporated. He joined QUALCOMM in April 1993, where he was first engaged in the system design and development of CDMA mobile station ASICs. Since 1997 he has been working on next-generation system designs for high-speed mobile wireless packet data services as one of the HDR co-project engineers. Prior to joining QUALCOMM he worked at Austek Microsystems in Adelaide, Australia on full custom VLSI designs for digital signal processing. He received his B.E. degree in electrical engineering from the University of Queensland, Australia, in 1985. He received his M.S.E.E. and Ph.D. degrees from Stanford University, California, in 1990 and 1993, respectively. He is a Fulbright Scholar and was awarded the University Medal by the University of Queensland in 1985. Additionally, he has been awarded several patents throughout his career.

MATTHEW S. GROB is vice president, engineering for Corporate Research and Development, QUALCOMM Incorporated. He joined QUALCOMM in August 1991. Since 1997 he has been HDR co-project engineer and is head of Corporate Research and Development, System Engineering. He was the Globalstar Air Interface editor and co-author of the Globalstar data services specification. In 1995 he was the project engineer for the CONDOR proof-of-concept program which demonstrated secure CDMA and AMPS voice with point-to-point and net broadcast modes. His additional contributions to QUALCOMM include direct involvement in CDMA data standards IS-99, IS-657, and IS-707, as well as being awarded several patents. He holds a B.S.E.E. from Bradley University, Peoria, Illinois as well as an M.S.E.E. from Stanford University.

ROBERTO PADOVANI received a Laureate degree from the University of Padova, Italy and a M.S. and Ph.D. degrees from the University of Massachusetts, Amherst in 1978, 1983, and 1985, respectively, all in Electrical and Computer Engineering. In 1984 he joined M/A-COM Linkabit in San Diego where he was involved in the design and development of satellite communication systems, secure video systems, and error-correcting coding equipment. In 1986 he joined QUALCOMM, Inc. where he is now a Senior Vice President of Corporate Research and Development. Dr. Padovani has been involved in the design, development, and standardization of IS-95 based systems. He holds 35 patents on wireless CDMA systems. He is an IEEE Fellow, and was a co-recipient of the 1991 IEEE Vehicular Technology Society Best Paper Award for a fundamental paper on the capacity of a CDMA cellular system.

NAGABHUSHANA T. SINDHUSHAYANA earned his undergraduate degree in electrical engineering from the Indian Institute of Technology (IIT), Madras, India, in 1989. He pursued his graduate study at Cornell University, Ithaca, New York, where he obtained his Master's and Ph.D. degrees in 1992 and 1995, respectively. He did his graduate work in the area of coded modulation and symbolic dynamics, under the guidance of Prof. Chris Heegard. He has been with Qualcomm since 1994, where he has been working on turbo codes and wireless communications, including the HDR packet data system.

ANDREW J. VITERBI is a co-founder of QUALCOMM Incorporated. He has spent equal portions of his career in industry, having also co-founded a previous company, and in academia as a professor of engineering first at UCLA and then at UCSD, at which he is now Professor Emeritus. His principal research contribution, the Viterbi Algorithm, is used in most digital cellular phones and digital satellite receivers, as well as in such diverse fields as magnetic recording, speech recognition, and DNA sequence analysis. In recent years he has concentrated his efforts on establishing CDMA as the multiple access technology of choice for cellular telephony and wireless data communication. He has received numerous honors both in the United States and internationally. Among these are three honorary doctorates and memberships in both the National Academy of Engineering and the National Academy of Sciences. He currently serves on the President's Information Technology Advisory Committee.

[7] *The temptation to charge per slot allocated should be in any case resisted, for the disadvantaged user who requires more slots is already paying the price of increased latency. Furthermore, if low-rate users predominate in a certain area, the provider will have the incentive to improve service by allocating a new microcell.*

CDMA/HDR: A Bandwidth-Efficient High-Speed Wireless Data Service for Nomadic Users

Paul Bender, Peter Black, Matthew Grob, Roberto Padovani, Nagabhushana Sindhushayana, and Andrew Viterbi, QUALCOMM, Incorporated

ABSTRACT

This article presents an approach to providing very high-data-rate downstream Internet access by nomadic users within the current CDMA physical layer architecture. Means for considerably increasing throughput by optimizing packet data protocols and by other network and coding techniques are presented and supported by simulations and laboratory measurements. The network architecture, based on Internet protocols adapted to the mobile environment, is described, followed by a brief discussion of economic considerations in comparison to cable and DSL services.

INTRODUCTION

The rapid growth and nearly universal coverage of industrialized nations and regions by digital wireless telephony gives rise to an increasing demand for data services as well. While current offerings are for data rates equivalent to those provided by wireline modems a decade or more ago, the gap is closing. Standards are already approved and chip sets are available for providing data rates above 64 kb/s within this calendar year (and century). Just beyond this horizon, however, service providers are already planning for wireless data rates above 2 Mb/s, approaching those of wireline, digital subscriber line (DSL), and cable. Whether such a wireless service can be made technically and economically competitive with wireline and cable is not the main issue, although we shall address this briefly in the last section. What will drive such a service is the demand for rapid low-latency availability of Internet access to nomadic users. In the next section we describe the characteristics and perceived needs of this user class. We then proceed to explore the characteristics of data requirements for speed and latency, after which we present a technical system solution tailored to these requirements and the characteristics of a specific implementation as an evolution of existing CDMA base station and subscriber terminal architectures. In the final section we briefly discuss the economics of such a system deployment.

CHARACTERISTICS OF NOMADIC USER DATA DEMAND

In business and the professions, the individual is often absent from her or his normal workplace. To continue to be productive on the road, both in transit and at business or professional meetings, connectivity to data at one's principal workplace and more broadly to other databases accessible through the Web is essential. Generally, members of this nomadic user class demand the same data service normally available in their home base. Often cited examples of the nature of such services are e-mail retrieval, Web browsing, ordering airline tickets, hotel reservations, obtaining stock quotes, and report retrieval, in such locations as airport lounges, hotel rooms, and meeting places, in each case without recourse to the limited or interface unfriendly facilities available in such places. In fact, one need not necessarily look beyond corporate boundaries; professional employees often spend nearly as much time in company conference rooms as in their own offices, and rarely are such rooms equipped with the number of ports needed to connect the majority of participants' laptops.[1]

The nature of such data traffic is decidedly asymmetric. A much higher forward (or downlink) rate is required from the access point (base station) than that generated by the access terminal (user terminal) in the reverse (uplink) direction. Furthermore, just as does the fixed user, the nomadic user expects a response to her or his request which does not suffer from excessive latency. Our goal is to satisfy these needs with an evolutional approach which minimizes the time and cost for providing such capabilities in existing cellular infrastructure and with terminals that differ only at digital baseband from existing cellular and personal communications systems (PCS) handsets.

[1] The obvious alternative of private campus wireless systems will be discussed in the last section.

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The Technical Challenge

Little information has been gathered on the exigencies of nomadic users and the networks to serve them, simply because, with the exception of a very small percentage of low-speed data service, such networks have not existed. On the other hand, with digital cellular networks in place for nearly a decade and with large numbers of mobile users served for several years, a great deal is known about the characteristics of digital wireless networks and their mobile users. A major step in the perfection of digital cellular technology was the development and standardization of code-division multiple access (CDMA) wireless systems and their adoption by the majority of North American, Korean, and Japanese carriers and manufacturers. Having proven its superiority to other access techniques, it is now being imitated (sometimes in a modified form) by most of the carriers and manufacturers who were the initial holdouts and skeptics of its viability.

CDMA was designed for efficient reverse (uplink) and forward (downlink) operations. It was initially widely believed that the reverse direction in which multiple users access each base station, hence representing multiple sources of interference with one another, would be the capacity limiting (or bottleneck) direction. This assumption turned out to be incorrect; the forward (downlink) was the initial bottleneck for three principal reasons:

- Interference on the reverse link enjoys the advantage of the law of large numbers, whereby the cumulative interference from multiple low-power transmitters tends to be statistically stable. The forward link, on the other hand, suffers interference from a small number of other high-power base stations. This becomes particularly serious at the vertices of the (imaginary) cellular hexagon where the transmitting base station and two other interfering base stations are equidistant from the intended user. This situation is relieved by soft handoff, where two or more base stations transmit to the user simultaneously.
- But soft handoff, while greatly diminishing interference, which itself increases capacity, still overall diminishes the forward link[2] capacity because an additional CDMA carrier must be assigned in the newly added base station. Depending on the region of (or criterion for) soft handoff, this can cause greater or lesser reduction.
- While on the reverse link, fast and accurate power control of multiple users is evidently critical to operation and capacity realization, it was initially felt in producing the first CDMA standard, cdmaOne (IS-95-A [1]), that forward link power control could be much slower. This turned out to reduce forward link capacity.

The second and third limiting causes have been eliminated or considerably diminished in the evolutionary revisions of cdmaOne (IS-95-B and CDMA2000). Fast power control is now implemented in the forward link, and the region of (criterion for) soft handoff has been diminished. The first cause (sometimes called the "law of small numbers"), remains, however. These improvements have brought the forward (downlink) capacity to parity with the reverse (uplink) capacity. But for high-speed data, such as downloading from the Internet, this is *not enough*. The downlink demand is likely to be several times greater than the uplink. The rest of this article deals with new approaches which will further increase the downlink capacity by a factor of three to four for data applications only.[3]

The Technical Approach to High-Speed Data

Most data applications differ fundamentally from speech requirements in two respects already noted, traffic asymmetry and tolerance to latency. Two-way conversational speech requires strict adherence to symmetry; also, latencies above 100 ms (which corresponds to about 1 kb of data for most speech vocoders) are intolerable. For high-speed data downlinked at 1 Mb/s, for example, 100 ms represents 100 kb or 12.5 kbytes; furthermore, latencies of 10 s are hardly noticeable, and this corresponds to a record of 1.25 Mbytes. Thus, smoothing over a variety of conditions, which is always advantageous for capacity, is easily accomplished.

All communication systems, wired as well as wireless, are greatly improved by a combination of techniques based on three principles:

- Channel measurement
- Channel control
- Interference suppression and mitigation

Our approach employs all three. First, on the basis of the received common pilot from each access point (or base station), each access terminal (subscriber terminal) can measure the received signal-to-noise-plus-interference ratio (SNR). The data rate which can be supported to each user is proportional to its received SNR. This may change continuously, especially for mobile users. Thus, over each user's reverse (uplink) channel, the SNR or equivalently the supportable data rate value is transmitted to the base station. In fact, since typically two or more base stations may be simultaneously tracked, the user indicates the highest among its received SNRs and the identity of the base station from which it is receiving it, and this may need to be repeated frequently (possibly every slot[4]). In this way the downlink channel is controlled as well as measured. Furthermore, by selecting only the best base station, in terms of SNR, to transmit to the user, interference to users of other base stations is reduced. Additionally, since data can tolerate considerably more delay than voice, error-correcting coding techniques which involve greater delay, specifically turbo codes, can be employed which will operate well at lower E_b/N_0, and hence lower SNR and higher interference levels.

Next, we show how unequal latency, for users of disparate SNR levels, can be used to increase throughput. Suppose we can separate users into N classes according to their SNR levels, and corresponding instantaneous rate levels supportable. Thus, user class n can receive slots at rate R_n b/s, where $n = 1.2..N$, and suppose the relative frequency of user packets of class n is P_n.

All communication systems, wired as well as wireless, are greatly improved by a combination of techniques based on three principles: channel measurement, channel control, and interference suppression and mitigation Our approach employs all three.

[2] *Although not the capacity of the reverse link, which soft handoff actually increases.*

[3] *Clearly voice is fundamentally a symmetric service, with stricter latency requirements, as we shall note below.*

[4] *In speech-oriented CDMA, voice frames are 20 ms long. In the next section, we shall establish corresponding lengths for data, which will be called slots. Multiplying* R_{av} *of (1) by slots per second yields throughput in bits per second.*

Data rate (kb/s)	Packet length (bytes)	FEC rate (b/sym)	Modulation
38.4	128	1/4	QPSK
76.8	128	1/4	QPSK
102.6	128	1/4	QPSK
153.6	128	1/4	QPSK
204.8	128	1/4	QPSK
307.2	128	1/4	QPSK
614.4	128	1/4	QPSK
921.6	192	3/8	QPSK
1228.8	256	1/2	QPSK
1843.2	384	1/2	8PSK
2457.6	512	1/2	16QAM

Table 1. *Various data rates.*

Suppose slots are assigned one at a time successively to each user class. Then the average rate, which we define as throughput, is

$$R_{av} = \sum_{n=1}^{N} P_n R_n \text{ b/s.} \qquad (1)$$

This, of course, means that lower-data-rate (and SNR) users will have proportionately higher latency. For if B bits are to be transmitted altogether for each class, the number of slots (and hence time) required for user class n will be B/R_n, and hence the latency L_n is inversely proportional to R_n.

Suppose, on the other hand, that we require all users to have essentially the same latency[5] irrespective of the R_n they can support. Then as each user class is served, it will be allocated a number of slots inversely proportional to its rate. Let F_n be the number of slots allocated to class n, where $F_n = k/R_n$, k being a constant. In this case, the average rate or throughput is

$$R'_{av} = \frac{\sum_{n=1}^{N} P_n R_n F_n}{\sum_{n=1}^{N} P_n F_n} = \frac{1}{\sum_{n=1}^{N} P_n / R_n} \text{ b/s.} \qquad (2)$$

In this case, however, the latency of all user classes will be the same (assuming the total number of bits K to be large and thus ignoring edge effects).

To assess the cost in throughput for equalizing latency, consider the extreme case of only two user classes, each equally probable ($P_1 = P_2 = 1/2$) but capable of supporting very disparate rates $R_1 = 16$ kb/s, $R_2 = 64R_1 = 1{,}024$ kb/s. Then in the first case, $R_{av} = 520$ kb/s. but $L_1/L_2 = 64$. In the second case, $L_1 = L_2$, but $R'_{av} = 31.51$ kb/s.

To see that there is a more rational allocation which is less "unfair" than a latency ratio of 64, and still achieves a better throughput than R'_{av}, consider a compromise which guarantees that the highest latency is no more than, for example, 8 times the lowest latency. Then in the second case, we would assign 8 slots to class 1 for every slot assigned to class 2. The result would be $L_1/L_2 = 8$ as required and

$$R_{av}'' = (8FP_1R_1 + FP_2R_2)/(FP_1 + FP_2) = 128 \text{ kb/s.}$$

For the general case of N classes and latency ratio L_{max}/L_{min}, it can be shown that the maximum achievable throughput, denoted by C, is

$$C = \frac{\sum_{n=1}^{n_o} P_n + \sum_{n=n_o+1}^{N} P_n (L_{min}/L_{max})}{\sum_{n=1}^{n_o} P_n / R_n + \sum_{n=n_o+1}^{N} (P_n/R_n)(L_{min}/L_{max})} \text{ b/s,} \qquad (3)$$

where $R_1 < R_2 \ldots R_N$ and n_o is such that $R_n \le C$ for all $n \le n_o$, while $R_n > C$ for all $n > n_o$.

Surprisingly, with this maximizing strategy, each user's latency is either L_{max} (for those for which $R_n < C$) or L_{min} (for those for which $R_n > C$). To determine the maximum throughput it is necessary to have a histogram of the achievable rates for users of the wireless network in question. This will be discussed in the next section. Also, as we shall find there, practical numerology considerations may require us to deviate from this strict bimodal latency allocation, although the ratio L_{max}/L_{min} will remain as the principal constraint.

Implementation of High-Data-Rate Code-Division Multiple Access

In the last section we discussed the key factors and parameters of a wireless system designed to optimize the transport of packet data. In the following we will describe such a system design, beginning first with a description of the air interface, to continue in the next section with a description of the network architecture. The design leverages in many ways the lessons learned from the development and operation of CDMA IS-95 networks, but makes no compromises in optimizing the air interface for data services. Furthermore, a compelling economic argument can be made for a design that can reuse large portions (to be exact, all but the baseband signal processing elements) of components and designs already implemented in IS-95 products, both in the access terminals and access points (APs).

Due to the highly asymmetric nature of the service offered, we will focus most of our attention on the downlink. In the IS-95 downlink, a multitude of low-data-rate channels are multiplexed together (with transmissions made orthogonal in the code domain) and share the available base station transmitted power with some form of power control. This is an optimal choice for many low-rate channels sharing a common bandwidth. The situation becomes less optimal when a low number of high-rate users share the channel. The inefficiencies increase further when the same bandwidth is shared between low-rate voice and high-rate data users, since their requirements are vastly different, as discussed previously. It should be noted that

[5] This is the case for voice. The only difference is that in speech, transmitter power levels are controlled to equalize received power, while here time, in terms of frames, is controlled to equalize energies.

increasing the bandwidth available for transmission cannot help in this regard if the data rate of the users is increased proportionally as well.

Therefore, a first fundamental design choice is to separate the services, that is, low-rate data (voice being the primary service in this category) from high-rate data services, by using possibly adjacent but nonoverlapping spectrum allocations. To summarize, a better system is one that uses an IS-95 or cdma2000-1X RF carrier to carry voice and a separate high-data-rate (HDR) RF carrier to deliver high-rate packet bursts.

With a dedicated RF carrier, the HDR downlink takes on a different form than that of the IS-95 designs. As shown in Fig. 1, the downlink packet transmissions are time multiplexed and transmitted at the full power available to the AP, but with data rates and slot lengths that vary according to the user channel conditions. Furthermore, when users' queues are empty, the only transmissions from the AP are those of short pilot bursts and periodic transmissions of control information, effectively eliminating interference from idling sectors.

The pilot bursts provide the access terminals with means to accurately and rapidly estimate the channel conditions. Among other parameters, the access terminal estimates the received E_c/N_t of all resolvable multipath components and forms a prediction of the effective received[6] SNR. The value of the SNR is then mapped to a value representing the maximum data rate such a SNR can support for a given level of error performance. This channel state information, in the form of a data rate request, is then fed back to the AP via the reverse link data rate request channel (DRC) and updated as fast as every 1.67 ms, as shown in Fig. 2. The reverse link data request is a 4-bit value that maps the predicted SNR into one of the data rate modes of Table 1. In addition, the access terminal requests transmission from only one sector (that with the highest received SNR) among those comprising the *active set*. Here the definition of active set is identical to that for IS-95 systems, but unlike IS-95, only one sector transmits to any specific access terminal at any given time.

The main coding and modulation parameters are summarized in Table 1.

The forward error correcting (FEC) scheme employs serial concatenated coding and iterative decoding, with puncturing for some of the higher code rates [2].

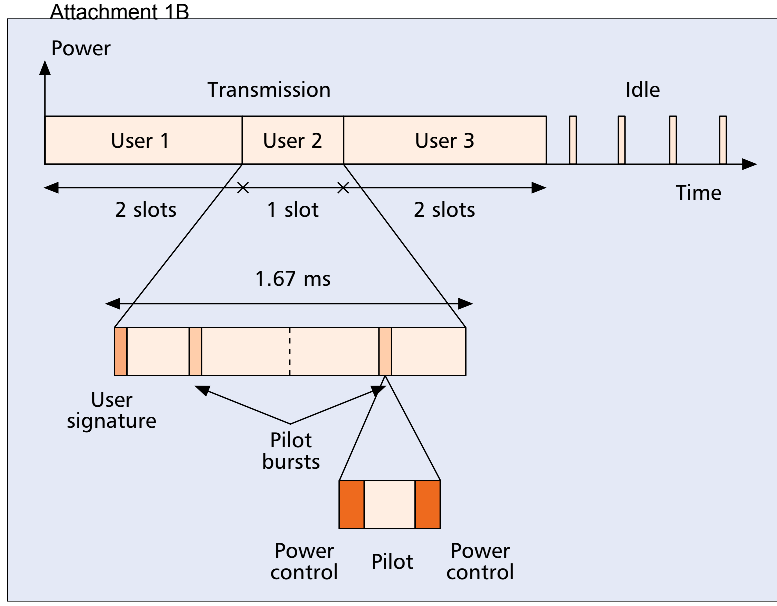

Figure 1. *An access point transmission diagram.*

Following the encoder, these traditional signal processing steps are applied: symbol repetition is performed on the lower-data-rate modes; scrambling, channel interleaving, and the appropriate modulation is applied to obtain a constant modulation rate of 1.2288 MHz for all modes. The in-phase and quadrature channels are then each demultiplexed into 16 streams, each at 76.8 kHz, and 16-ary orthogonal covers are applied to each stream. The resulting signal, obtained by adding the 16 data streams, is then spread by quadrature pseudonoise (PN) sequences, bandlimited and upconverted. The resulting RF signal has the same characteristics as an IS-95 signal, thus allowing the reuse of all analog and RF designs developed for IS-95 base stations, including the power amplifiers, and the receiver designs for subscriber terminals.

Table 2 summarizes the SNR required to achieve a 1 percent packet error rate (PER).

Note that at the lower rates this corresponds to $E_b/N_0 \approx 2.5$ dB, a result of using iterative decoding techniques on serial concatenated codes, while for the two highest rates, E_b/N_0 increases considerably because 8-phase shift keying (PSK) modulation and 16-quadrature amplitude modulation (QAM) are employed. These were obtained both by bit-exact simulation and

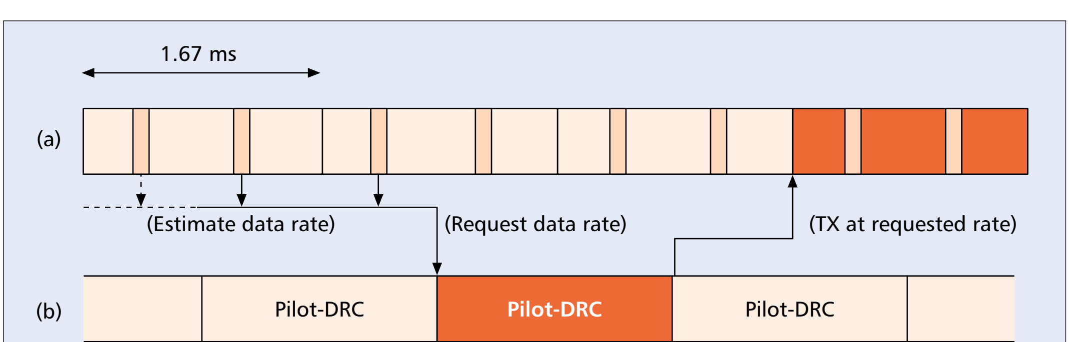

Figure 2. *A channel estimation and data request channel timing diagram: a) access terminal receive; b) access terminal transmit.*

[6] E_c *represents the received signal energy density and* N_t *represents the total nonorthogonal single sided noise density.* N_t *comprises intercell interference, thermal noise, and possibly nonorthogonal intracell interference.*

corroborated by laboratory measurements with a complete RF link.

At this point we are able to estimate the maximum achievable throughput per sector as discussed in the previous section. Figure 3a shows a graph of the cumulative distribution function of the SNR for a typical embedded sector of a large three-sector network deployed with a frequency reuse of one. In particular, the SNR values are those of the best serving sector and representative of a uniform distribution of users across the coverage area. From the results of Fig. 3a and the knowledge of the SNR required to support a given data rate (Table 1), it is straightforward to derive the histogram of data rates achievable in such an embedded sector. The result is shown in Fig. 3b where the SNRs used in the calculation are those of Table 1 with an additional 2 dB of margin to account for various losses. Finally, Fig. 3c shows the realized throughput per sector per 1.25 MHz of bandwidth versus the parameter L_{max}/L_{min}. Note that the throughput is doubled for a latency ratio $L_{max}/L_{min} = 8$.

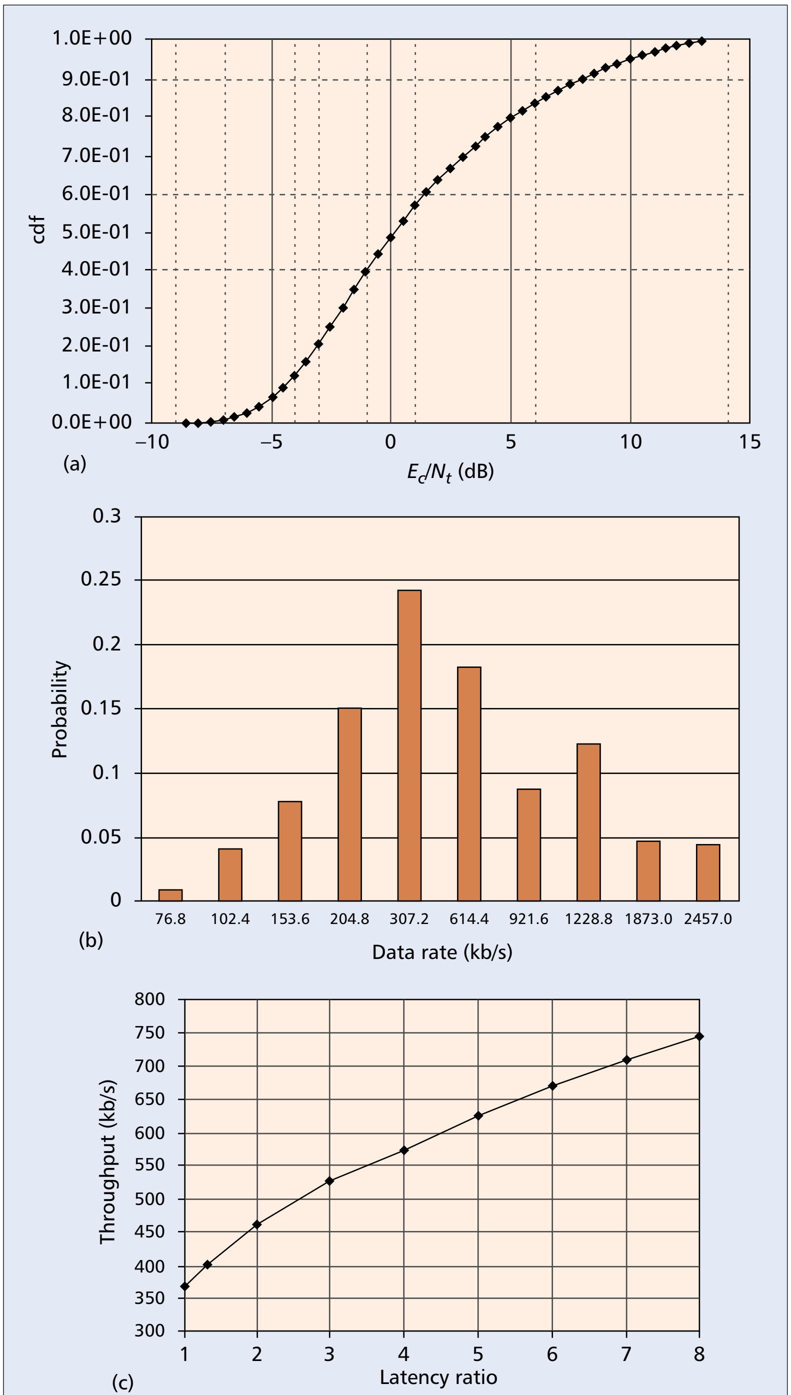

Figure 3. *a)* E_c/N_t *distribution for a typical embedded sector in a three-sector network with universal frequency reuse in each cell; b) data rate histogram; c) sector throughput vs. latency ratio* L_{max}/L_{min}.

NETWORK ARCHITECTURE

Since the radio link has been designed to provide efficient access to packet data networks, it is natural to turn to the most ubiquitous packet data network — the Internet — when selecting the network architecture. Adopting Internet protocols in the communication between the access terminal and the access network allows users to access the widest variety of information and services, including e-mail, private intranets, and the World Wide Web. Furthermore, the selection of Internet protocols in the design of the access network allows the access network equipment to take advantage of the ever decreasing costs and increasing performance of Internet equipment.

First, we examine the communication link between the access terminal and the access network. Figure 4a shows the protocol stack used in such a link.

In order to carry traffic between the user and the network, we need to select a network-layer protocol. We chose the Internet Protocol (IP) [3] because it is the network-layer protocol of the Internet. The Internet carries its network-layer protocol over a variety of transports. For example, asynchronous transfer mode (ATM) often carries Internet traffic on the Internet backbone, Ethernet often carries Internet traffic on local area networks (LANs), and the Point-to-Point Protocol (PPP) [4] often carries Internet traffic over dialup connections. We chose PPP for the following reasons. First, PPP is widely supported. Moreover, PPP allows the transport of a variety of network-layer protocols, supports methods for

Data rate (kb/s)	E_c/N_t (dB)
38.4	–12.5
76.8	–9.5
102.6	–8.5
153.6	–6.5
204.8	–5.7
307.2	–4.0
614.4	–1.0
921.6	1.3
1228.8	3.0
1843.2	7.2
2457.6	9.5

Table 2. *SNR for a 1 percent packet error rate.*

differing quality of service (QoS) requirements, and also supports methods for authentication. Lastly, PPP has low overhead, an important feature for a wireless transport.

It is well known that the Internet carries different types of traffic with different QoS requirements. Some traffic, such as Transmission Control Protocol (TCP) [5] traffic, tends to be more sensitive to errors and less sensitive to delay. Other traffic, such as Real-Time Transport Protocol (RTP) [6] traffic, tends to be more sensitive to delay and less sensitive to errors. In order to support these differing QoS constraints over a single physical link between two Internet nodes (e.g., routers or personal computers), many nodes insert traffic with different QoS requirements into different queues. Then, by servicing the queues based on the different QoS requirements, the node attempts to provide the QoS desired by the different types of traffic. For PPP sessions, multiple queues over a single physical link are supported using the PPP Multilink Protocol (MP) [7]. In this configuration each queue is carried by a different PPP link. This feature allows PPP to support differing QoS requirements. For instance, in the example shown in Fig. 4a the system has negotiated three PPP links.

Since radio link bandwidth is a limited resource, we should consider protocol overhead when choosing a protocol that will be carried over the radio link. PPP has been designed to minimize its own protocol overhead. In addition, it supports the compression of network-layer protocol headers such as TCP and IP/UDP/RTP header compression, further reducing the overhead of carrying user traffic over radio links.

It is typical to operate HDR with a received signal-to-noise ratio that results in a physical-layer PER of approximately 1 percent. This error rate is significantly higher than the error rate seen on most wireline networks. Since most network protocols and most network applications were designed assuming wireline error rates, the wireless link error rate needs to be reduced. The most straightforward method of reducing the error rate is for access terminals to operate at a higher signal-to-noise ratio regime. However, the increase in the signal-to-noise ratio required to reach wireline error rates results is a substantial decrease in overall throughput. A more efficient method for decreasing the error rate of the wireless link is obtained by implementing a form of automatic repeat request (ARQ). HDR implements a negative acknowledgment (NACK)-based radio link protocol (RLP) whereby incorrectly received blocks of data are detected and then retransmitted. This allows PPP and the higher layers to operate at an error rate regime similar to that experienced in wireline networks.

As shown in Fig. 4a, each PPP link may be carried by a separate RLP stream. In this specific example the system has negotiated three separate RLP streams to carry the three PPP links. This introduces the flexibility of allowing for finer control of the QoS. For instance, depending on the QoS requirement, different transmit scheduling policies with differing priorities may be implemented on some PPP streams. Additionally,

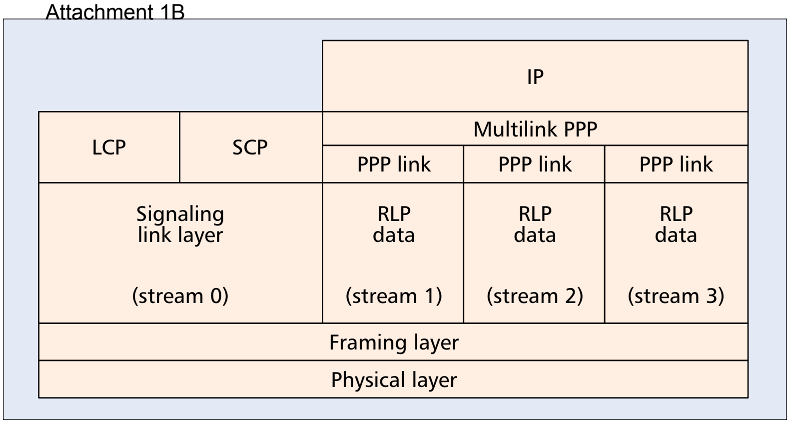

Figure 4a. *The air interface protocol stack — an example.*

RLPs with different effective error rates may be used on other PPP links. The framing layer shown in Fig. 4a is responsible for multiplexing the separate RLP streams into one physical layer.

In addition to user traffic, the HDR radio link must support the transport of signaling messages. The model for the transport of signaling streams is based on PPP. Signaling is partitioned into two basic types: the Link Control Protocol (LCP) and Stream Control Protocol (SCP). Similar to the PPP LCP, the LCP is used to negotiate radio link protocols and options at the start of the session and to control the radio link during the session. For example, the LCP is used at the start of the session to negotiate the link layer authentication type that will be used for the duration of the session. Similar to the PPP Network Control Protocol (NCP), the SCP is used to carry stream-specific signaling messages. For example, SCP is used to transmit the RLP NACKs upon detection of missing RLP data.

In the remainder of this section we discuss in which elements of the network the various layers of the protocols may be implemented. First we will describe the implementation on the user side of the air interface, to be followed by a brief description of the network side.

On the user side of the air interface reside two basic functional elements: the access terminal and the computer. These elements may reside in two devices, as in the case of a wireless HDR modem connected to a portable computer, or may be combined into a single device such as a wireless personal digital assistant (PDA). In the latter case, the device must implement the entire protocol stack, while in the former the protocol stack implementation may be partitioned in two ways.

In the first partitioning method, the access terminal implements the entire protocol stack. This partitioning is sometimes referred to as the *network model*. When using this partitioning, the access terminal and computer may physically be connected over Ethernet, through a PCMCIA interface, or over the Universal Serial Bus (USB). Figure 4b shows the layering endpoints of the network model.

In the second partitioning method, the access terminal implements the entire protocol stack with the exception of PPP and everything above PPP, *A first fundamental design choice is to separate the services, that is, low-rate data (voice being the primary service in this category) from high-rate data services, by using possibly adjacent but non-overlapping spectrum allocations.*

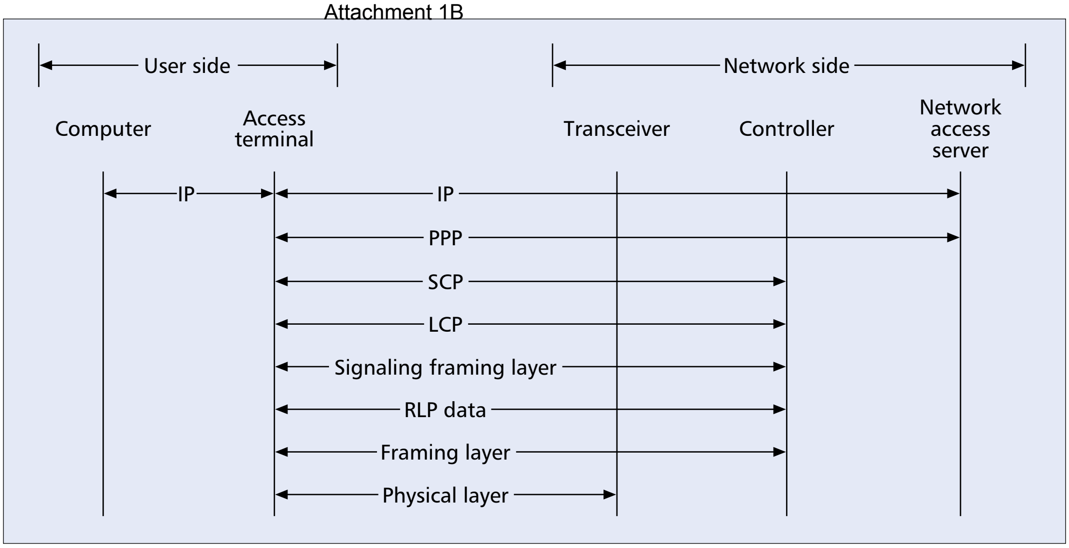

Figure 4b. *Air interface protocol endpoints — the network model.*

while the computer implements PPP and all protocols above PPP. This partitioning is sometimes referred to as the *relay model*. In the relay model, the access terminal and computer may be physically connected via RS-232 or USB. Figure 4c shows the layering endpoints of the relay model.

The network side of the air interface is modeled on the traditional Internet network access server (NAS) [8]. There are three basic functional elements: the transceiver, the controller, and the NAS. The transceiver implements the physical layer. The controller implements the framing layer, the RLP data layer, the signaling link layer, and all layers above the signaling link layer. The three functional blocks communicate over IP using open interfaces. The NAS implements the PPP layer and all layers above PPP. Figures 4b and 4c show the layering endpoints for the partitioning.

In our design of the access network, the access point implements the transceiver, the controller, and the NAS functional elements. The network interface implements the protocols and interfaces needed to connect the access point to an IP network and a backhaul network. Since the transceiver, controller, and NAS communicate over IP using open interfaces, there is no strict requirement for all the elements to be located in the access point. For example, in a more traditional cellular implementation, one might choose to centralize the controller and the NAS.

Only the transceiver and controller are specific to the radio link. The NAS and network interface are standard equipment used by today's Internet service providers (ISPs). By using an interface such as the widely supported Layer Two Tunneling Protocol (L2TP) between the NAS and the modem pool controller, it is possible to use this standard ISP equipment for many applications.

With the exception of other access points, the access point communicates with all elements in the access network using widely deployed Internet protocols. In addition, the access point transports all traffic using IP. Therefore, with the exception of the access point itself, all equipment in an access network is readily available Internet equipment.

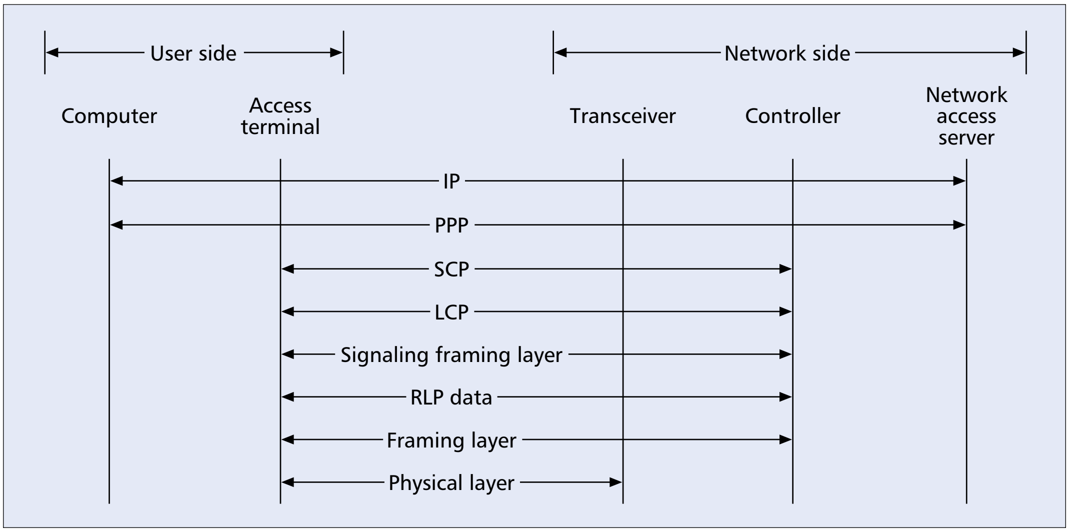

Figure 4c. *Air interface protocol endpoints — the relay model.*

ECONOMICS AND TARIFF CONSIDERATIONS

We consider finally the critical issue of the value of the service and how to establish tariffs. For truly nomadic users, constant travelers, people who prefer to work on their patio, at the beach or on the slopes, and so on, the service is most valuable and cannot be compared with high-speed wireline services provided by DSL or cable modems. At the other extreme for strictly fixed users, whose offices or homes are connected by fiber or wireline/cable services, the economics usually favor the latter. Suppose, however, that a carrier must decide between a wireline/cable high-speed solution or the wireless approach of this article. Here capital expenditures and possible tariff considerations dominate. The problem for wireless is that established wireline services have already conditioned users to expect a flat monthly rate essentially independent of the amount of service. The idealized economic model for digital packet-based wireless, practical considerations aside, will be to charge for usage on a packet basis.[7]

Most likely, however, most users will constitute a population of varying degrees of nomadicity, but even the occasional nomad will grow to depend on the flexibility and continuity provided by the "anywhere, anytime" nature of wireless connectivity. If this indeed turns out to be the case, even private networks (LANs) may be supplanted by wireless HDR usage. Economies of scale would seem to favor the HDR microcell located in or near a corporate campus over the private network. In fact, the best architecture for the latter may coincide with that of the former. Were this to occur, fiber, wire, and cable pipes may be relegated to the backbone and to the occasional supercomputer node, with the last kilometer or less becoming universally wireless for the majority of users.

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BIOGRAPHY

PAUL BENDER is vice president of technology for Corporate Research and Development of QUALCOMM Incorporated. He received his Ph.D. in electrical engineering in 1992 with an emphasis on communications theory and systems at the University of California, San Diego (UCSD). He joined QUALCOMM in August 1992 and has contributed his expertise to the development of innovative CDMA digital communications at QUALCOMM. His responsibilities have included building the system test team and leading the system engineering team for the (IS-95) cellular and PCS infrastructure. He is currently involved in the development of QUALCOMM's High Data Rate (HDR) technology. Prior to joining QUALCOMM, he conducted research in signal processing for digital recording at UCSD's Center for Magnetic Recording Research. In addition, he assisted students in designing and debugging basic analog circuits for the Electrical and Computing Engineering Department at UCSD.

PETER J. BLACK is vice president of technology for Corporate Research and Development, of QUALCOMM Incorporated. He joined QUALCOMM in April 1993, where he was first engaged in the system design and development of CDMA mobile station ASICs. Since 1997 he has been working on next-generation system designs for high-speed mobile wireless packet data services as one of the HDR co-project engineers. Prior to joining QUALCOMM he worked at Austek Microsystems in Adelaide, Australia on full custom VLSI designs for digital signal processing. He received his B.E. degree in electrical engineering from the University of Queensland, Australia, in 1985. He received his M.S.E.E. and Ph.D. degrees from Stanford University, California, in 1990 and 1993, respectively. He is a Fulbright Scholar and was awarded the University Medal by the University of Queensland in 1985. Additionally, he has been awarded several patents throughout his career.

MATTHEW S. GROB is vice president, engineering for Corporate Research and Development, QUALCOMM Incorporated. He joined QUALCOMM in August 1991. Since 1997 he has been HDR co-project engineer and is head of Corporate Research and Development, System Engineering. He was the Globalstar Air Interface editor and co-author of the Globalstar data services specification. In 1995 he was the project engineer for the CONDOR proof-of-concept program which demonstrated secure CDMA and AMPS voice with point-to-point and net broadcast modes. His additional contributions to QUALCOMM include direct involvement in CDMA data standards IS-99, IS-657, and IS-707, as well as being awarded several patents. He holds a B.S.E.E. from Bradley University, Peoria, Illinois as well as an M.S.E.E. from Stanford University.

ROBERTO PADOVANI received a Laureate degree from the University of Padova, Italy and a M.S. and Ph.D. degrees from the University of Massachusetts, Amherst in 1978, 1983, and 1985, respectively, all in Electrical and Computer Engineering. In 1984 he joined M/A-COM Linkabit in San Diego where he was involved in the design and development of satellite communication systems, secure video systems, and error-correcting coding equipment. In 1986 he joined QUALCOMM, Inc. where he is now a Senior Vice President of Corporate Research and Development. Dr. Padovani has been involved in the design, development, and standardization of IS-95 based systems. He holds 35 patents on wireless CDMA systems. He is an IEEE Fellow, and was a co-recipient of the 1991 IEEE Vehicular Technology Society Best Paper Award for a fundamental paper on the capacity of a CDMA cellular system.

NAGABHUSHANA T. SINDHUSHAYANA earned his undergraduate degree in electrical engineering from the Indian Institute of Technology (IIT), Madras, India, in 1989. He pursued his graduate study at Cornell University, Ithaca, New York, where he obtained his Master's and Ph.D. degrees in 1992 and 1995, respectively. He did his graduate work in the area of coded modulation and symbolic dynamics, under the guidance of Prof. Chris Heegard. He has been with Qualcomm since 1994, where he has been working on turbo codes and wireless communications, including the HDR packet data system.

ANDREW J. VITERBI is a co-founder of QUALCOMM Incorporated. He has spent equal portions of his career in industry, having also co-founded a previous company, and in academia as a professor of engineering first at UCLA and then at UCSD, at which he is now Professor Emeritus. His principal research contribution, the Viterbi Algorithm, is used in most digital cellular phones and digital satellite receivers, as well as in such diverse fields as magnetic recording, speech recognition, and DNA sequence analysis. In recent years he has concentrated his efforts on establishing CDMA as the multiple access technology of choice for cellular telephony and wireless data communication. He has received numerous honors both in the United States and internationally. Among these are three honorary doctorates and memberships in both the National Academy of Engineering and the National Academy of Sciences. He currently serves on the President's Information Technology Advisory Committee.

Most users will likely constitute a population of varying degrees of nomadicity, but even the occasional nomads will grow to depend on the flexibility and continuity provided by the "anywhere, anytime" nature of wireless connectivity.

[7] *The temptation to charge per slot allocated should be in any case resisted, for the disadvantaged user who requires more slots is already paying the price of increased latency. Furthermore, if low-rate users predominate in a certain area, the provider will have the incentive to improve service by allocating a new microcell.*

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Highly Sectorized System for Internet Wireless Access

Elvino S. Sousa
University of Toronto
(sousa@comm.utoronto.ca)

Abstract

The conceptual design of a system for Internet wireless access based on a large number of antenna sectors or fixed beams, with an overlapping structure, is proposed. The system utilizes spread spectrum modulation with time division multiplexing for transmissions from different overlapping antenna sectors. The fixed antenna beam structure is a practical approach to achieve space division multiplexing capacity gains with modest complexity. The time division multiplexing structure is shown to be a solution to the more general problem of designing sets of orthogonal signals for overlapping antenna sectors. We introduce the concept of time re-use as an analogue of frequency re-use in order to allocate time slots to clusters of antenna sectors. A frequency/time allocation strategy that depends on the terminal position within the cell and reduces interference is also introduced.

1.0 Introduction

Recently we have undergone a very successful deployment of 2nd generation wireless communication systems such as GSM, IS-95, and IS-136. At the same time we are on the verge of the introduction of third generation systems which have been standardized under the ITU IMT-2000 process. These third generation systems will provide greater bit rates than those achievable with 2nd generation systems including rates up to 384 Kbps. However, other than the bit rates these networks have characteristics that are similar to 2G systems in the sense that they are circuit switching oriented and have relatively low capacity. These networks have been designed to operate in environments that are similar to cellular in the sense that they support mobility at vehicular speeds through multi-path propagation environments. On the other hand there is currently a great deal of interest in providing wireless Internet access to support IP oriented applications [1] [2]. In most cases these services would be provided to portable fixed terminals such as notebook PC's. It becomes advantageous to design these networks to support the IP oriented services in an efficient manner that is packet switching oriented. In this paper we discuss the characteristics of a wireless network that fulfils the requirements of high capacity and packet switching for Internet access.

A chief characteristic of any wireless system that achieves very high spectral efficiencies (capacity) is the utilization of highly sectorized antennas that re-use the spectrum to a very high degree. Another main characteristic is that a modulation scheme with a large number of bits/Hz of spectral efficiency must be used. Such a system must also be highly efficient in terms of a multiple access scheme. In this paper we describe the architecture of a system which achieves such a high spectral efficiency/capacity. The system architecture consists of an antenna architecture consisting of a set of overlapped fixed beams with a relatively narrow beam width. In this paper we consider the forward link of such a system. The modulation scheme is designed to exhibit a high degree of robustness so as to withstand inter-beam interference. On the other hand the modulation scheme needs to be more spectrally efficient on a single user basis than standard spread spectrum schemes such as those implemented in IS-95 and WCDMA. The multiple access scheme also must have a high degree of spectral efficiency utilizing an appropriate hybrid of orthogonal and non-orthogonal spreading. This paper discusses the design of a joint antenna architecture, modulation, multiple access, and frequency resource allocation scheme to implement such a system.

2.0 Antenna Systems

An efficient antenna system is a fundamental requirement to achieve high capacity. Possible approaches to the design of antenna systems, in order of increasing complexity, are as follows: fixed horn antennas, switched beam antenna, fully adaptive beam forming antennas, and adaptive beam forming in conjunction with multi-user receivers that separate the signals in time and in space. The design of a fully adaptive beam forming antenna that tracks the position of individual terminals is still a complex task. We propose an approach where a set of fixed beam antennas are used. A large number of beams with overlapping coverage is used. The transmission on the different beams is scheduled depending on the degree of inter-beam interference. A robust modulation technique is employed in order to handle inter-beam interference. Beams with a degree of interference greater than a given threshold will employ strictly orthogonal signals, whereas beams with a degree of interference less than the threshold will employ robust modulation such as obtained with some form of spread spectrum. An intelligent, low overhead, hand-off algorithm is required to determine the beam to use in the transmission to a given terminal.

The set of beams from a set of base stations should be designed to cover a service area. A backbone network will dynamically route the packets to the optimum base station in case where the terminal is located in an area of overlapping coverage from beams in different base stations. Antenna beams corresponding to co-located transmitters and beams from transmitters on different cells should be considered in

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the transmission scheduling algorithm/hand-off using a unified framework.

We consider a system with a large number of sectors/beams per cell in comparison to standard cellular systems, e.g. 12 - 60 or greater number of sectors per cell. In this architecture there is a strong interplay of beam switching and TDM multiplexing schemes. Together with the scheduling algorithm, this gives rise to the concept of time re-use as a generalization of the well known concept of frequency re-use of cellular systems. The antenna system architecture can be categorized by a set of parameters that can be optimized in a given system design as follows:

- number of antenna beams per base station, or beam angle.
- interbeam interference/overlap threshold: this threshold will define the degree of interference at which we consider two beams to overlap, alternatively we may define the concept of hard overlap vs. soft overlap.
- shape of beams: optimize shape to adjust for traffic loading and facilitate hand-off. Beams should be distorted in the direction of motion of the terminal in order to minimize the number of hand-offs.
- roll-off: beams should have a fast roll-off versus angle in order to minimize inter-beam interference, or soft overlap.
- beam overlap degree: beams should be designed to overlap. That is, for a given coverage area there are multiple beams that can be used. The selected beam depends on scheduling issues determined by the set of neighbouring terminals that require service.

3.0 Modulation

Given the limited spectrum, we need a scheme with high spectral efficiency such as multi-level QAM. However, given the large number of sectors/beams per cell and the resulting many antenna sidelobes we need a modulation scheme with robustness against interference (soft-overlap).

Spread spectrum fills the interference suppression requirement, but lacks the required high spectral efficiency as a modulation scheme. There are two main approaches to modulation:

1) non-spread spectrum: design a spectrally efficient modulation scheme (QAM, 16QAM, 64QAM), and then re-use the spectrum in the different cells/sectors according to a frequency re-use plan as is typically done in non-CDMA cellular systems using the concept of frequency re-use cluster size. The frequency re-use cluster size depends on the robustness, or level of modulation. Modulation schemes such as BPSK and QPSK will have a greater robustness to co-channel interference than higher level QPSK schemes, and can therefore possibly operate with smaller frequency re-use cluster sizes.

2) spread spectrum-like scheme: Consider MQAM but with the basic signalling pulse not the sinc pulse but a spread spectrum signal (i.e. a sequence of N sinc pulses determined by a PN code). This scheme has a processing gain equal to N. Thus, there is a bandwidth expansion equal to N. We may reclaim the lost spectral efficiency by using orthogonal spreading codes (K) in a so-called multi-code approach. We may use any number of codes up to $K = M$. With N spreading codes this scheme has a spectral efficiency equal to the non-spread scheme, but has the property that it is robust against co-channel interference in the sense that the co-channel interference behaves as white noise at the receiver.

The number of orthogonal codes that we decide to utilize, K, and the size of the modulation alphabet M ($M = 2$ for binary) depends on the level of inter-cell interference and degree of multi-path propagation. For a cell with little multi-path choosing K also only affects inter-cell interference. Thus, for hot spot traffic scenarios this modulation scheme can attain the spectral efficiency of regular MQAM. We refer to this modulation scheme as spread QAM (N-MQAM-K), where M is the size of the modulation alphabet, N is the spreading factor (processing gain), and K is the loading degree (number of orthogonal codes used). One possible set of spreading codes is the set of Walsh functions with a randomization code (for noise whitening) as used in 2G and 3G CDMA.

For modest processing gains, N, large chip rates, and significant multi-path, the above modulation scheme may suffer from inter-symbol interference. An alternative approach to the standard use of equalizers is to modify the scheme into multicarrier. We may refer to this generalized modulation scheme as multicarrier N-MQAM-K, where the number of sub-carriers is another parameter for system optimization.

4.0 Overlapping Antenna Beams

In current cellular systems cells with 3 or 6 sectors are typically utilized. In the case of ideal antennas for one cell systems and systems employing CDMA the capacity is typically proportional to the number of sectors in the cell. For example, in an idealized one-cell IS-95 system with 3 sectors, each Walsh function can be re-used 3 times in the cell. We now consider a system with a set of overlapping sectors as shown in Figure 1. The system consists of two sets of 3 sectors with one of the sets rotated by 60° with respect to the other. Three of the sectors are shown in solid lines and three in dotted lines. A simultaneous transmission in the solid X, Y, and dotted z, y sectors will result in service to terminals in the intersections of

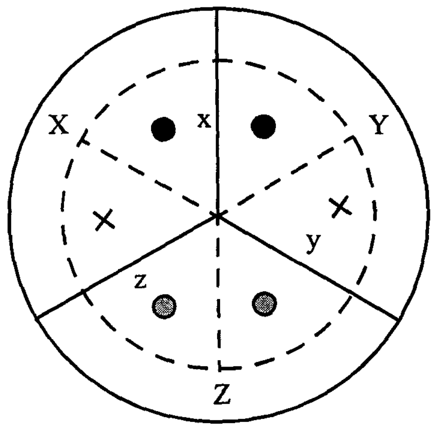

FIGURE 1. System with six overlapping sectors: X, Y, Z are conventional 120° sectors corresponding to the solid line. x, y, z are overlapping 120° sectors corresponding to the dotted line. Transmit simultaneously in X, Y, z, y: Serve terminals in Xx, Yx, Zz, and Zy. Capacity equals 4/3 with respect to non-overlapping, 3 sector system.

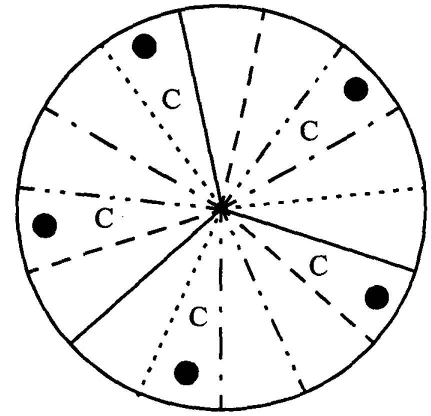

FIGURE 2. Overlapping sectorized antenna system: 120 degree sectors, rotation step size of 24 degrees. Each point is covered by 5 sectors. The sectors labelled with "C" can share the same channels. Capacity increase over conventional 120 degree systems equals 5/3.

the sectors Xx, Yx, (heavy shaded circle), and Zz, Zy (light shaded circle). Terminals in Xz, Yy can not be served at the same time as there will be collisions. With this scheme the capacity of the system increases by a factor of 4/3 over a system with 3 sectors, under idealized conditions of uniform traffic over all the sectors. For a system with 6 non-overlapping 60°-sectors, the capacity would of course be larger, but the technique of overlapping sectors can be used for any sector size and ultimately there is a lower limit on the sector size.

For the above system the degree of overlap is equal to 2. Each point is covered by two sectors. We may increase the degree of overlap to a larger value. In Figure 2 we show a system with 120° sectors where the degree of overlap is equal to 5. In this system a given channel resource can be re-used up to five times as opposed to the 3 times for the 120° system with no overlap for users in specific locations. For example in Figure 2 the diagram contains 15 non-overlapping regions. Any set of 5 contiguous regions defines a sector in the system (120°). Users in a given region are served by the sector containing that region as its center region. If we take the sectors with center regions shown as "C" in the figure, then users in the regions labelled as "C" can be served using the same channel or code in these 5 sectors, without interference, in the ideal case. This system has a capacity that is greater than the 120° degree system with no overlap by a factor of 5/3.

We may further increase the above degree of overlap. In the limit we may hypothesize a system where the antennas have a fixed sector angle but the antenna can be rotated by any angle. That is, each user is allocated an individual antenna whose beam is centered on the given user. Such a system will have a capacity that is greater than the conventional system with 3 non-overlapping sectors by a factor of 2 [3].

5.0 Orthogonal Signals for Overlapping Beams

In the above we have considered the number of times that a given channel/code can be used in a cell. We now consider the design of signals for the simultaneous use of a number of users. The standard design for the forward link for the well known multiple access schemes (FDMA, TDMA, CDMA) is a set of orthogonal signals for any number of users that simultaneously transmit in the same sector. In CDMA the standard design is a set of Walsh functions. However, the same set of Walsh functions is not assigned to adjacent sectors since the antenna patterns are not ideal and contain sidelobes. The Walsh functions are randomized with the pilot sequence, with different sequence offsets assigned to different sectors. As a result the signals on one sector appear random with respect to the signals on adjacent sectors.

In the case of overlapping sectors we need to find sets of orthogonal signals to assign to the different sectors such that signals assigned to users in an overlapping sector are also orthogonal. For the case of overlap with degree 2, as in Figure 1, and without the randomization requirement, we could for example assign the odd and even Walsh functions to the 6 overlapping 60° half sectors, in an alternating pattern. However this scheme does not work if we attempt to randomize the spreading codes (Walsh functions) as we do in CDMA systems. The requirement for signal design is

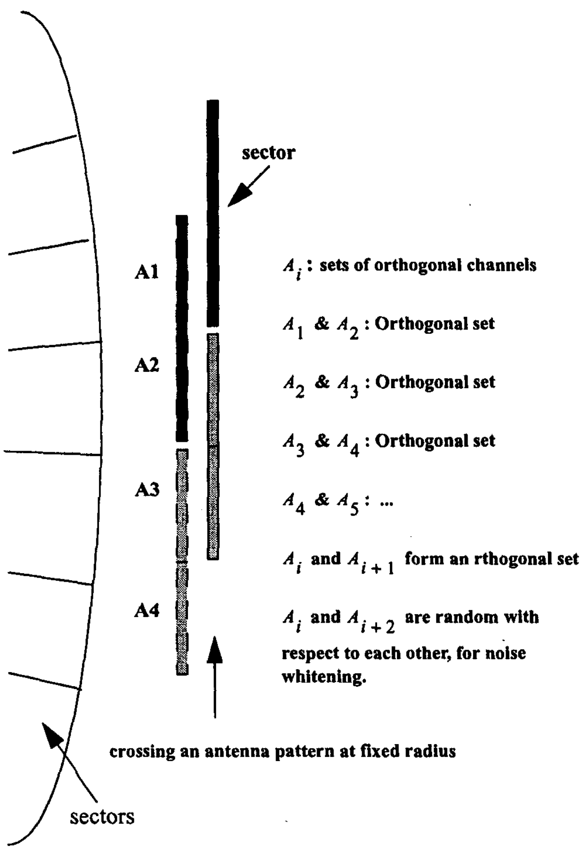

FIGURE 3. Design of orthogonal signals and corresponding allocation to overlapping sectors.

illustrated in Figure 3. If we take the example in Figure 1, there are 6 intersecting sector regions. Any two adjacent regions forms a sector, which must be assigned a set of orthogonal signals. In Figure 4 we show the design of the orthogonal signals for a system with overlapping sectors

with overlap degree equal to 3. Orthogonality between signals is created in two steps. In the first step we partition the whole channel resource into three (orthogonal) time slots which are to be assigned to three contiguous sector intersection regions. In the second step we create orthogonal signals within each of the time slots to allocate to different users in a sector intersection region. If we assign colours to these time slots, the time slot allocation problem then amounts to a colouring problem for the different sector intersection regions (e.g. 6 regions in Figure 1). Now, in order to avoid interference due to non-ideal antenna patterns the orthogonal signals for any two regions assigned the same colour should be designed to be random with respect to each other. For example, this could be done by

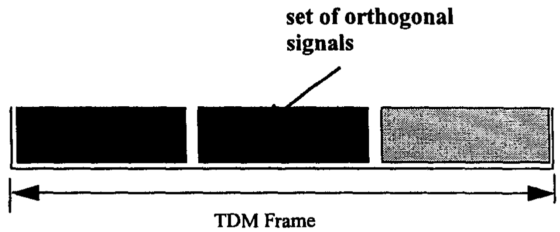

FIGURE 4. Design of orthogonal signals for use in system with overlapping sectors.

the process of randomization of Walsh functions as is done in 2G and 3G CDMA systems.

There are a number of alternatives in designing orthogonal signals for the different users in an intersection region referred to above. The principle approaches are code division multiplexing (CDM) as in 2G and 3G CDMA, or strictly time division multiplexing (TDM) with a robust modulation technique which can be some form of spread spectrum as defined above. In this case the different users in an intersecting region are assigned sub-slots in a given slot. The CDM approach may have the advantage of equalizing the inter-cell interference somewhat by maintaining a more constant interference level. Also in the relatively rare cases of a fast time varying channel, the CDM approach may allow for SNR gains due to time diversity. On the other hand, the purely TDM approach has the advantage that transmission occurs to one terminal at a time. The system can be designed to make adjustments on a time sub-slot basis in order to optimize transmission for a given terminal.

6.0 Time Re-use

The above procedure for the design of orthogonal signals for overlapping sectors amounts to a time re-use algorithm in the case that time domain orthogonality based on TDM is chosen. Time slots within a TDM frame can be allocated to different overlapping sectors using a pattern similar to a frequency re-use pattern in narrow-band cellular networks. This gives rise to the concept of time re-use as the analogue of frequency re-use.

The design of the time re-use algorithm starts with an interference threshold, where if the interference of the signals from two sectors is greater than the threshold we say that the two sectors overlap, otherwise we say that the sectors do not overlap. At a given position in the coverage area there will be a number of overlapping sectors which we denote by the parameter n. The actual number of overlapping sectors may be variable throughout the service area. We assume that n is the maximum number of overlapping sectors over all areas. We may refer to this set of overlapping sectors as a sector cluster in an analogous manner as we do for frequency re-use cell cluster.

We then introduce a TDM frame structure with N slots in the frame. We allocate time slots to sectors to obtain a time re-use pattern using a similar algorithm to frequency re-use algorithms. A similar TDM scheme for a sectorized antenna system was introduced in [6].

7.0 Position Dependent Frequency/Time Assignment

Internet wireless access systems will most likely serve fixed or slowly moving terminals. As a result it becomes feasible to assign frequency/time resources to terminals depending on their position in a cell. One such scheme [5] is illustrated in Figure 5 where we have partitioned the frequency/time resource into three sets (e.g. 3 time slots) and denoted each by a different "colour" or pattern in the figure. The idea is that in a cellular type of system most of the interference in the forward link occurs at terminals that are located in the cell boundary. As such it is advantageous to ensure that terminals at the boundaries of adjacent cells be assigned orthogonal time/frequency resources. In a typical non-CDMA cellular system we typically assign a set of different channels to these cells, leading to the concept of frequency re-use cluster size. The capacity of the system is inversely proportional to the frequency re-use cluster size. In the case of a robust spread spectrum modulation scheme, as we propose here, we can effectively operate with a cluster size of one and reduce interference considerably compared to the standard case where frequency/time assignment is independent of position.

For simplicity the frequency/time assignment in Figure 5 has been shown for a system employing omnidirectional antennas. This scheme can easily be generalized for a sectorized system.

8.0 Conclusions

We have discussed some of the issues in the conceptual design of the forward link of a system for Internet wireless access. In order to achieve high capacities the system utilizes a large number of antenna sectors or fixed beams at each base station. The system utilizes a mixture of orthogonal (hard orthogonality) and statistically orthogonal (soft orthogonality) signals allocated to the different sectors depending on whether they are or are not considered to overlap respectively, based on an interference threshold criteria. In the proposed design we prefer the choice of time division multiplexing to achieve the hard orthogonality. A robust modulation scheme based on spread spectrum is proposed to achieve the soft-orthogonality.

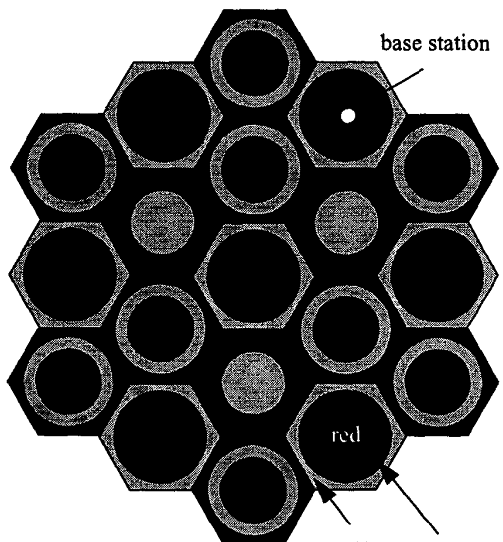

FIGURE 5. Position dependent frequency/time assignment.

We propose a frequency/time allocation scheme that is dependent on the position of the terminal within the cell.

9.0 References

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